MHD-pumped, high-speed ingestion of plasma from wall gas source into spheromak interior: Observations and model

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US-Japan CT Workshop,

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Santa Fe, NM

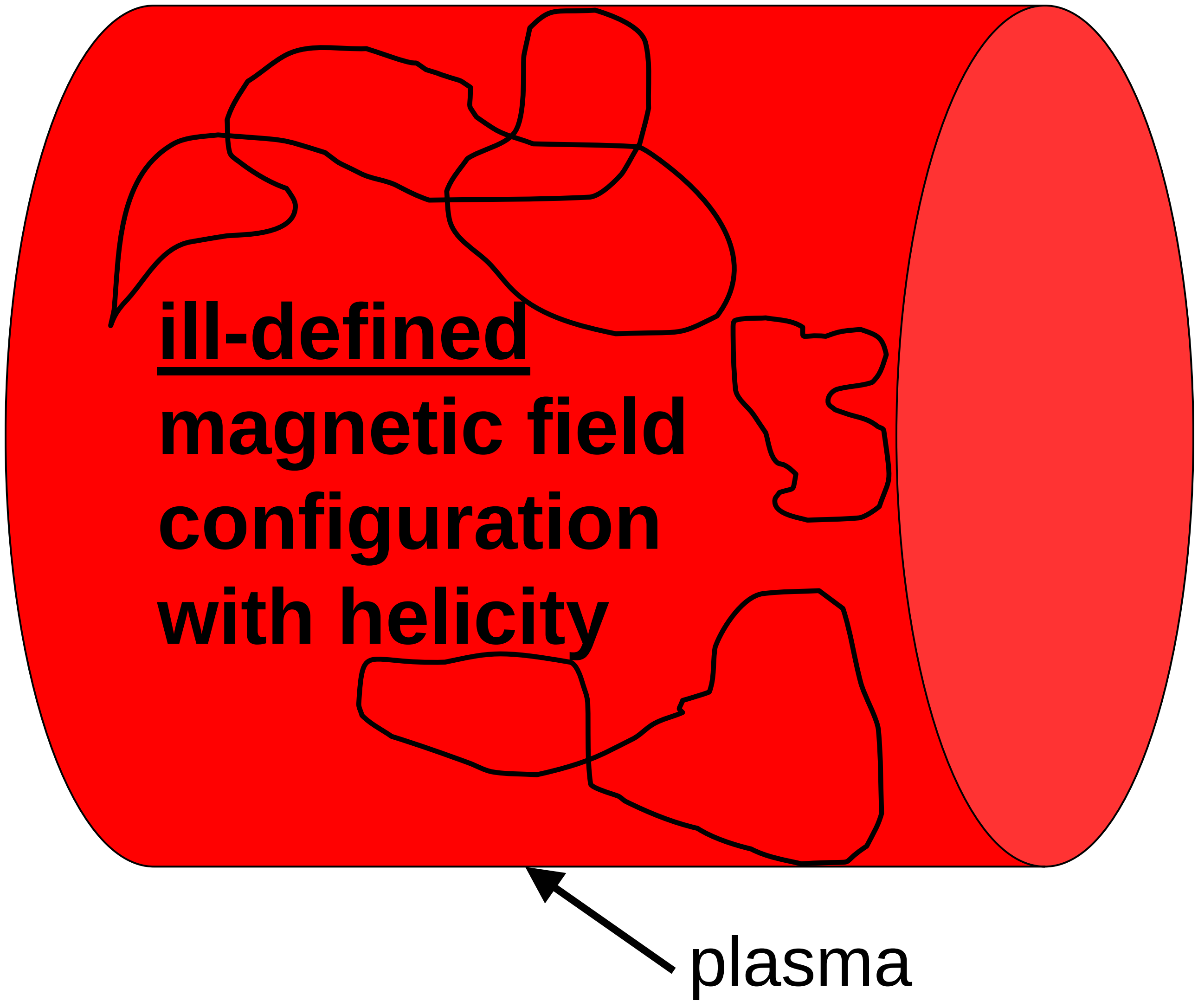
Taylor Relaxation:

"*magical process*" whereby magnetic fields spontaneously self-organize into a magnetic confinement configuration

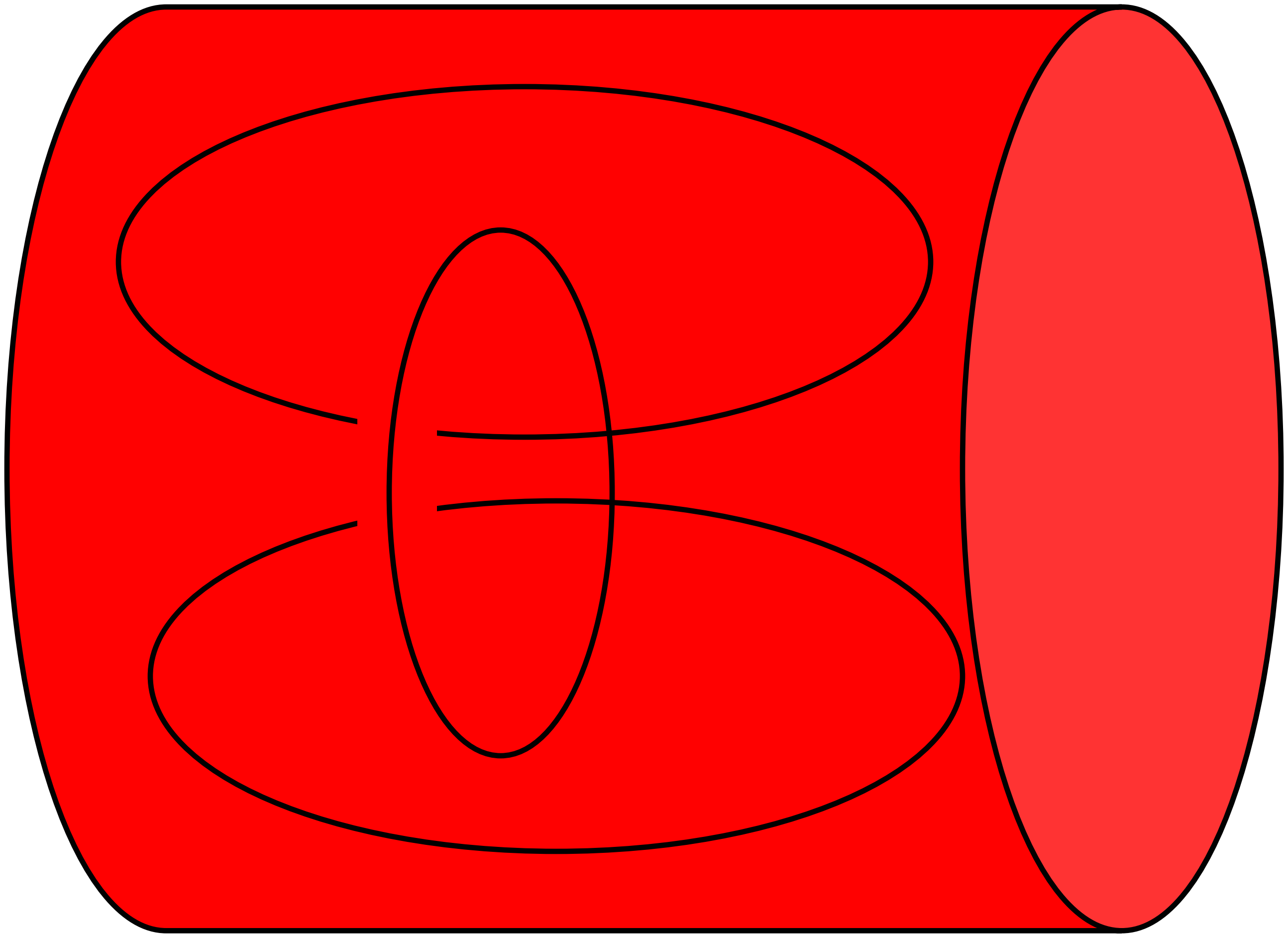
-energy minimized

-helicity conserved

Taylor Relaxation initial condition:



Taylor Relaxation final condition: **spheromak**



Axisymmetric magnetic confinement configuration

Relaxation conserves helicity

Issues in Taylor relaxation

1) Plasma is just “there”
   - but how did plasma get in?

2) Uniform pressure (zero beta)
   - but need pressure gradients for confinement

3) Symmetry
   - but Cowling’s theorem shows that symmetry must be broken to create poloidal flux

4) Relaxation changes topology to spheromak
   - but how does topology evolve?

Goal: address these issues

Method: build <u>simplest</u> helicity injection system and follow fast dynamics in detail

<u>Helicity injection requirement:</u>

voltage-biased electrodes must link magnetic flux

(helicity injection rate $=2V\Psi$)

<u>Simplest system</u>

1. coaxial, co-planar electrodes
2. gas puff valves

Results

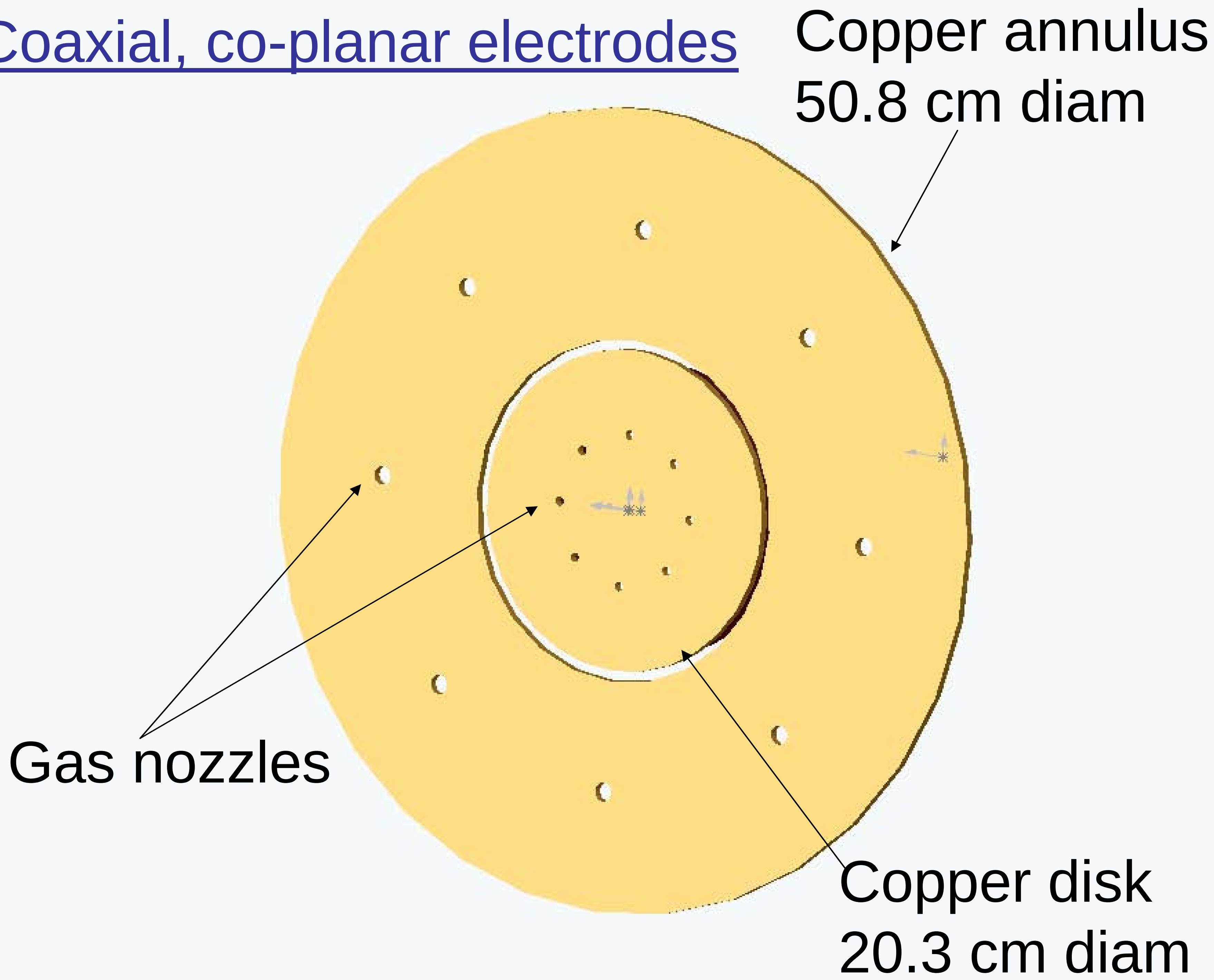
1. **<u>Find kink instability is fundamental to relaxation and to topological evolution</u>**
   - toroidal to poloidal flux conversion (Hsu/Bellan 2003)
   - basic mechanism for relaxation to spheromak

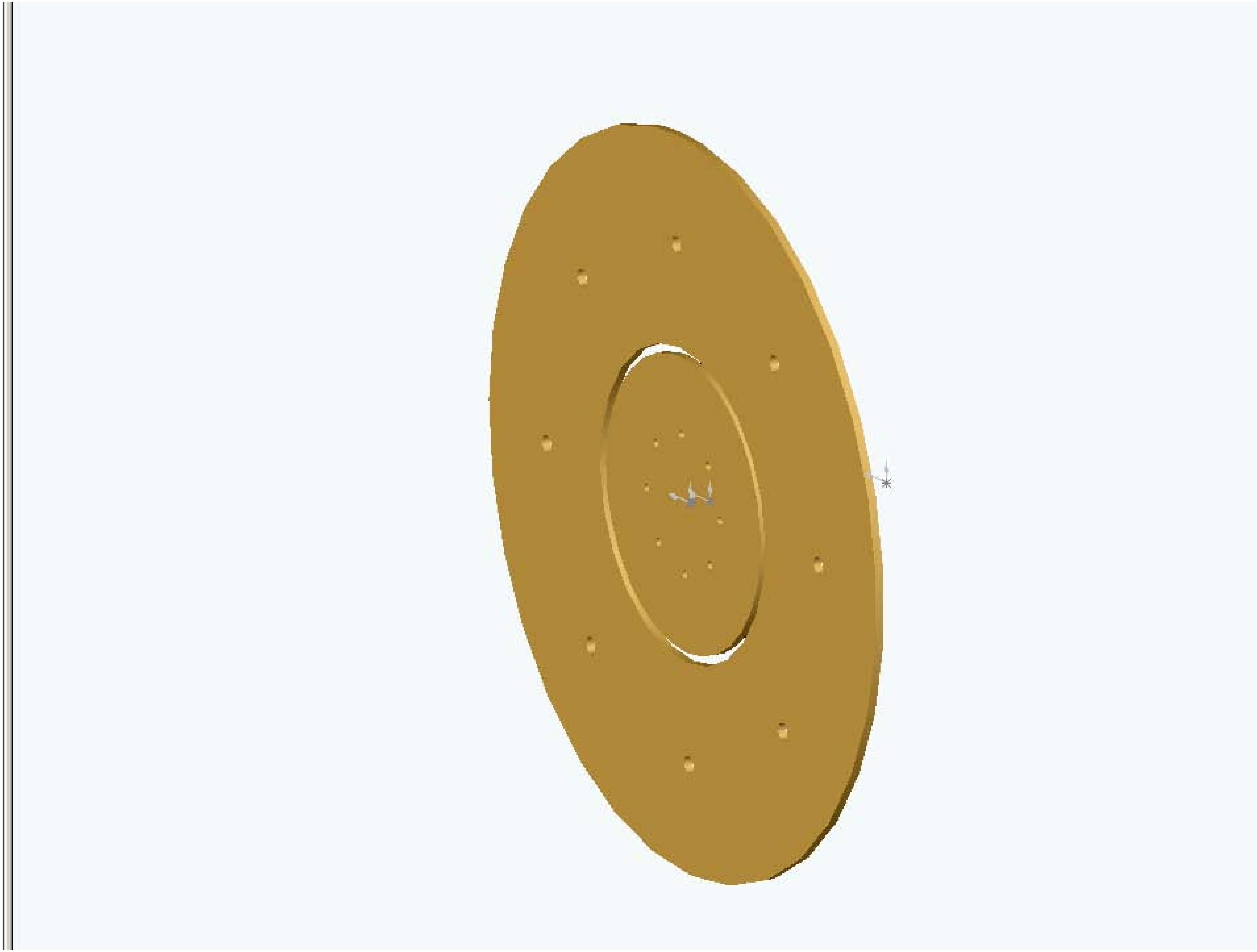
2. **<u>Find high speed plasma inflows (jets) are a critical feature</u>**
   - driven by **J**x**B** forces which *ingest* plasma from *wall source*
   - inflow velocity ~v_A, 10-10^2 times neutral gas acoustic velocity
   - gas source geometry critically affects plasma geometry
   - closely related to astrophysical jets

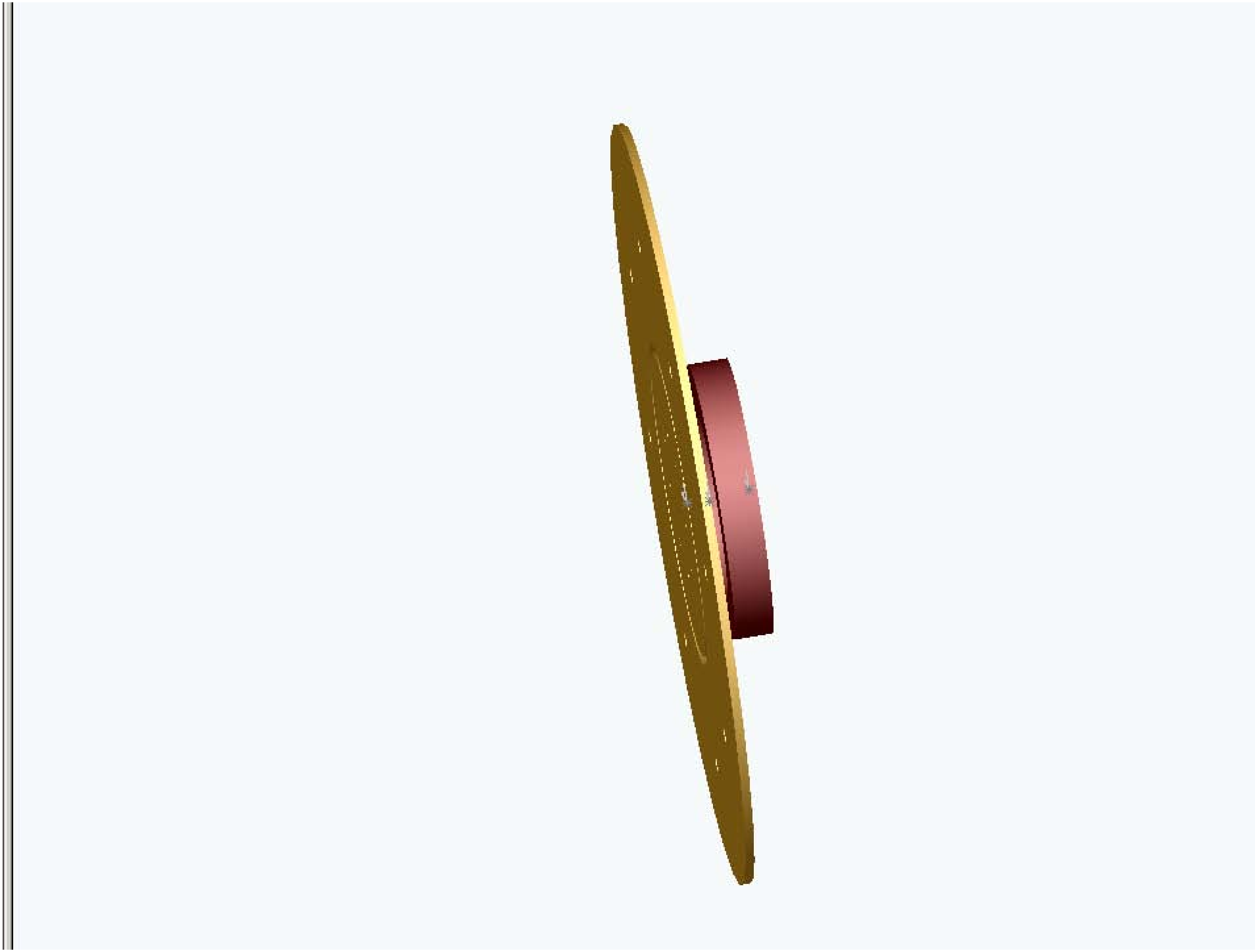
3. **<u>Find uniform plasma assumption is inappropriate</u>**
   - stagnation of flow gives jet collimation, extremely high localized density
   - get bright, dense, *collimated* flux tubes

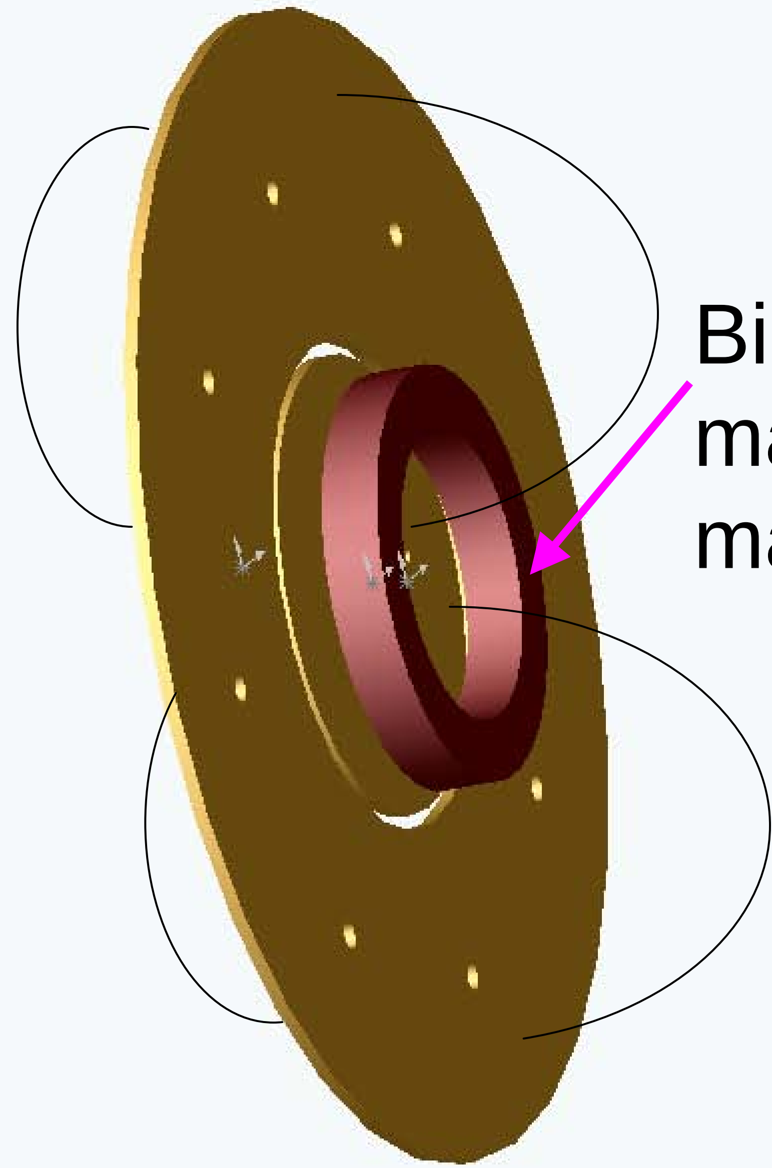
Experimental Setup

Coaxial, co-planar electrodes

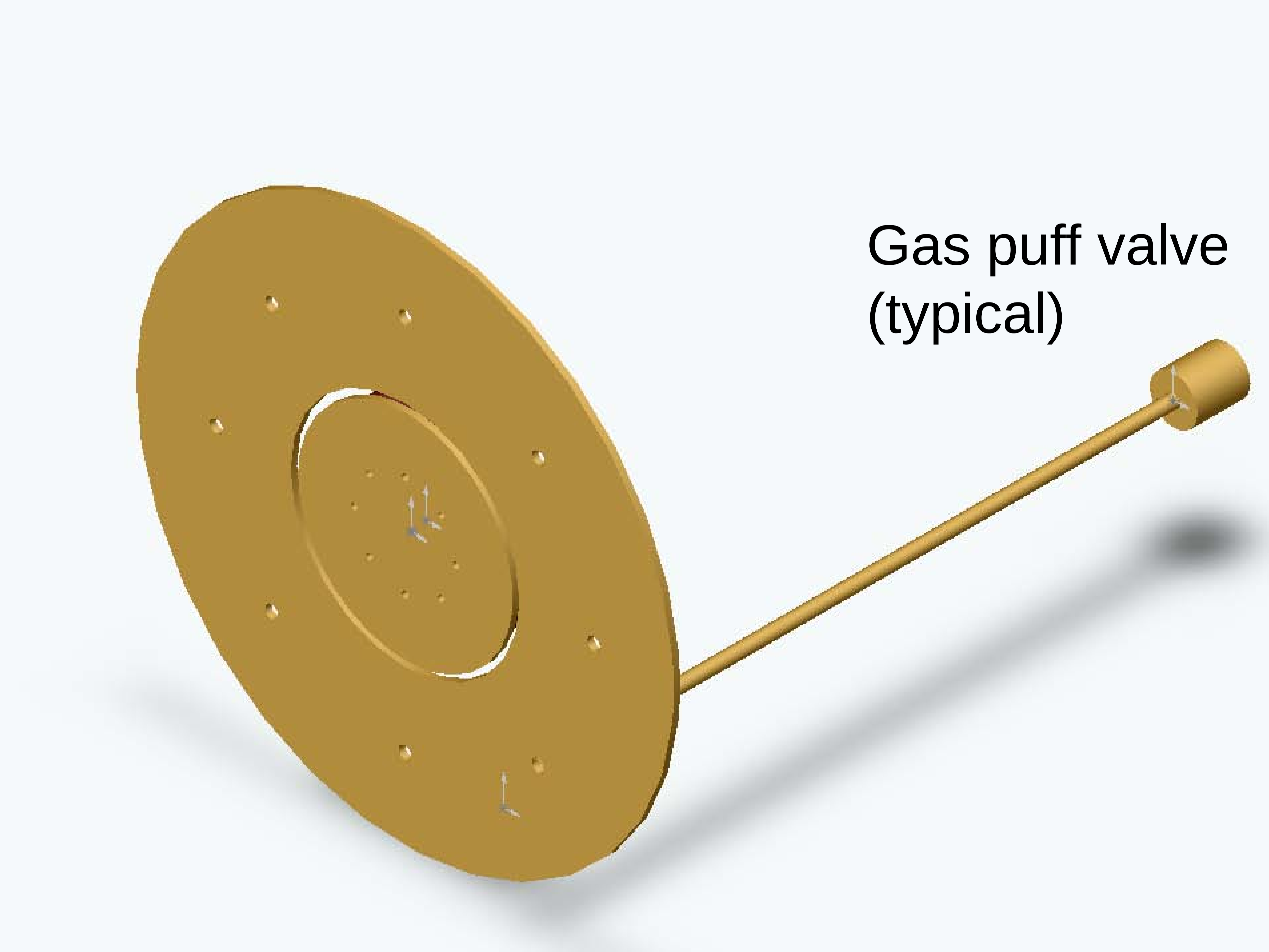


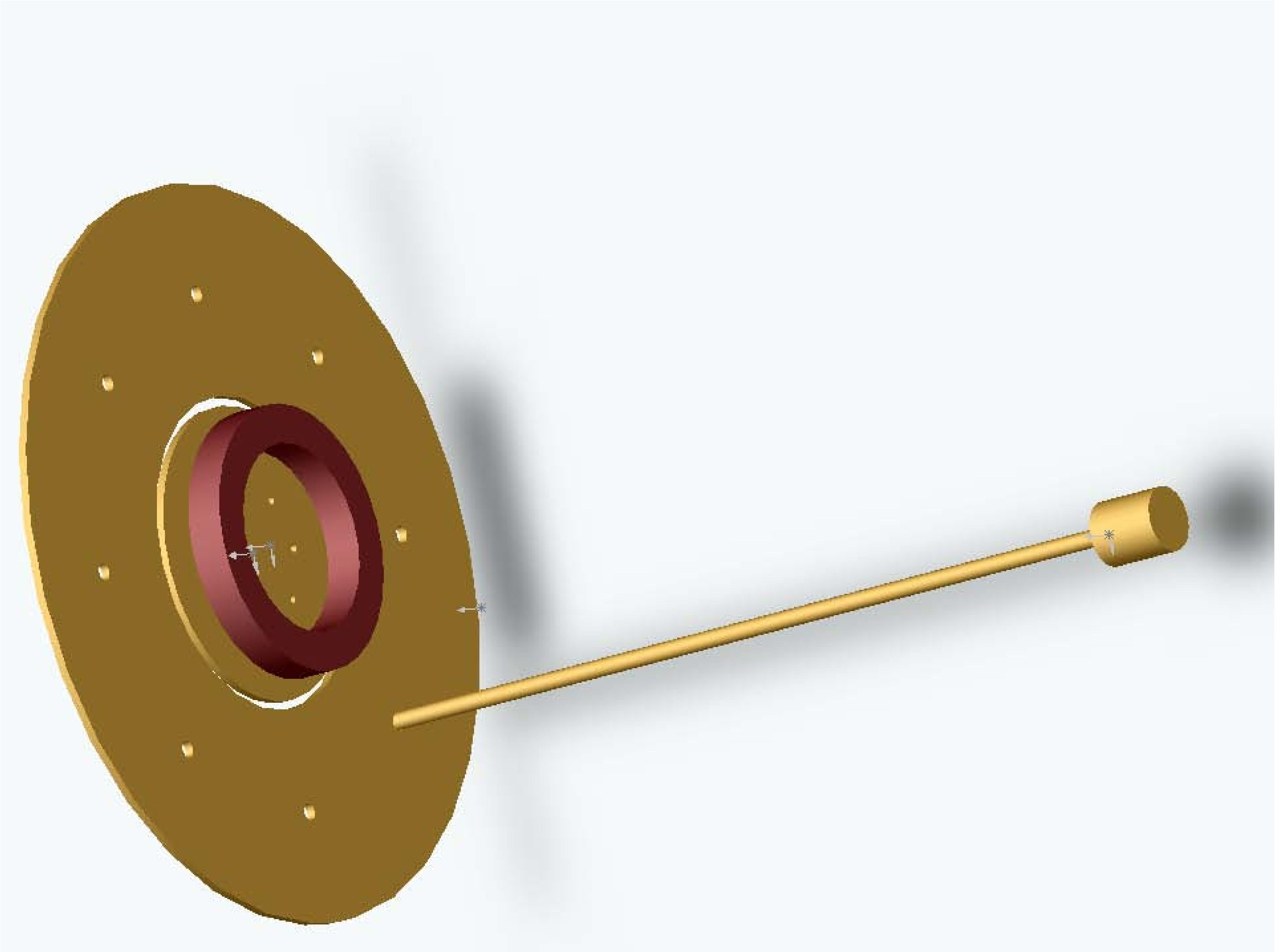


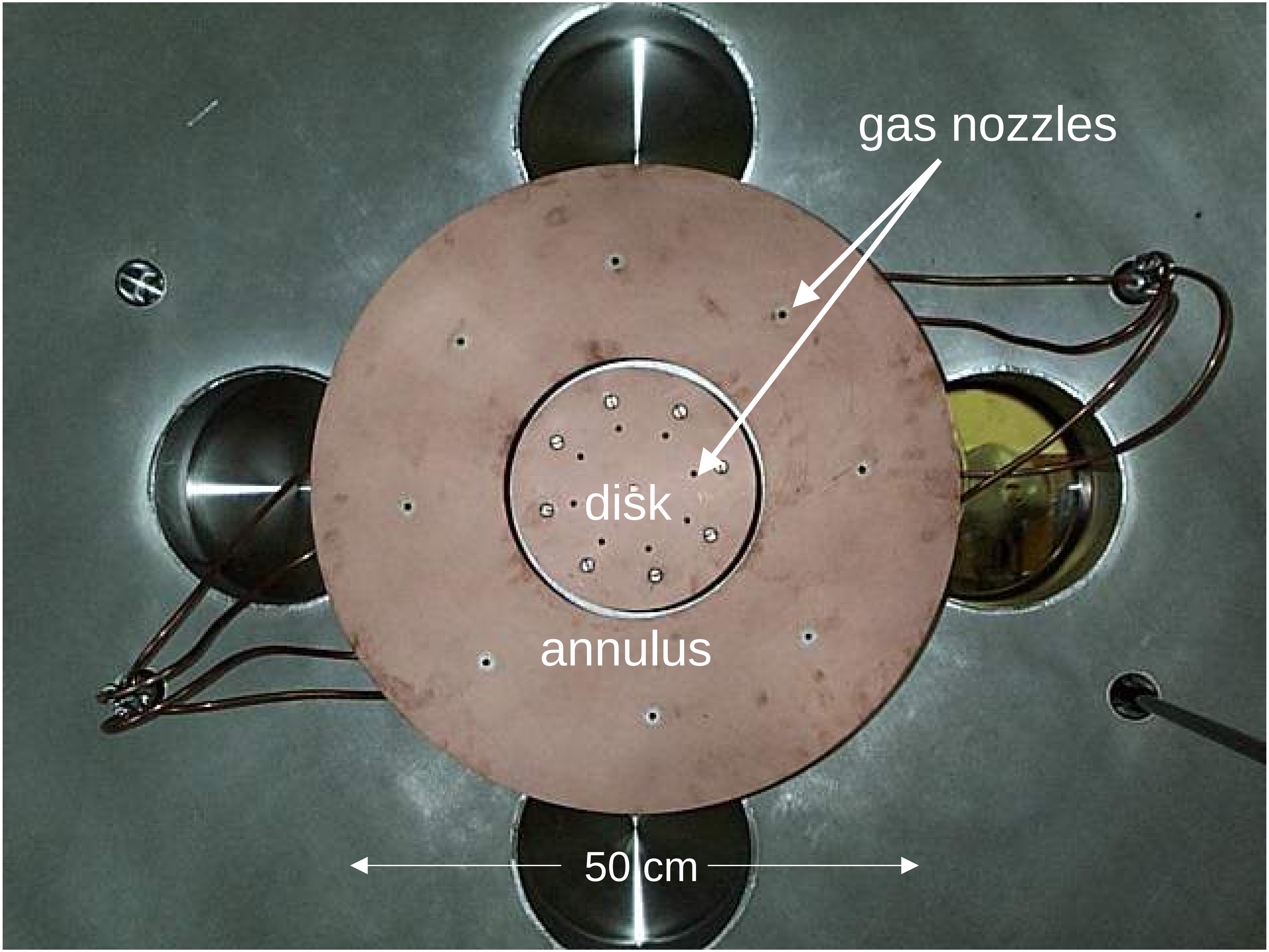




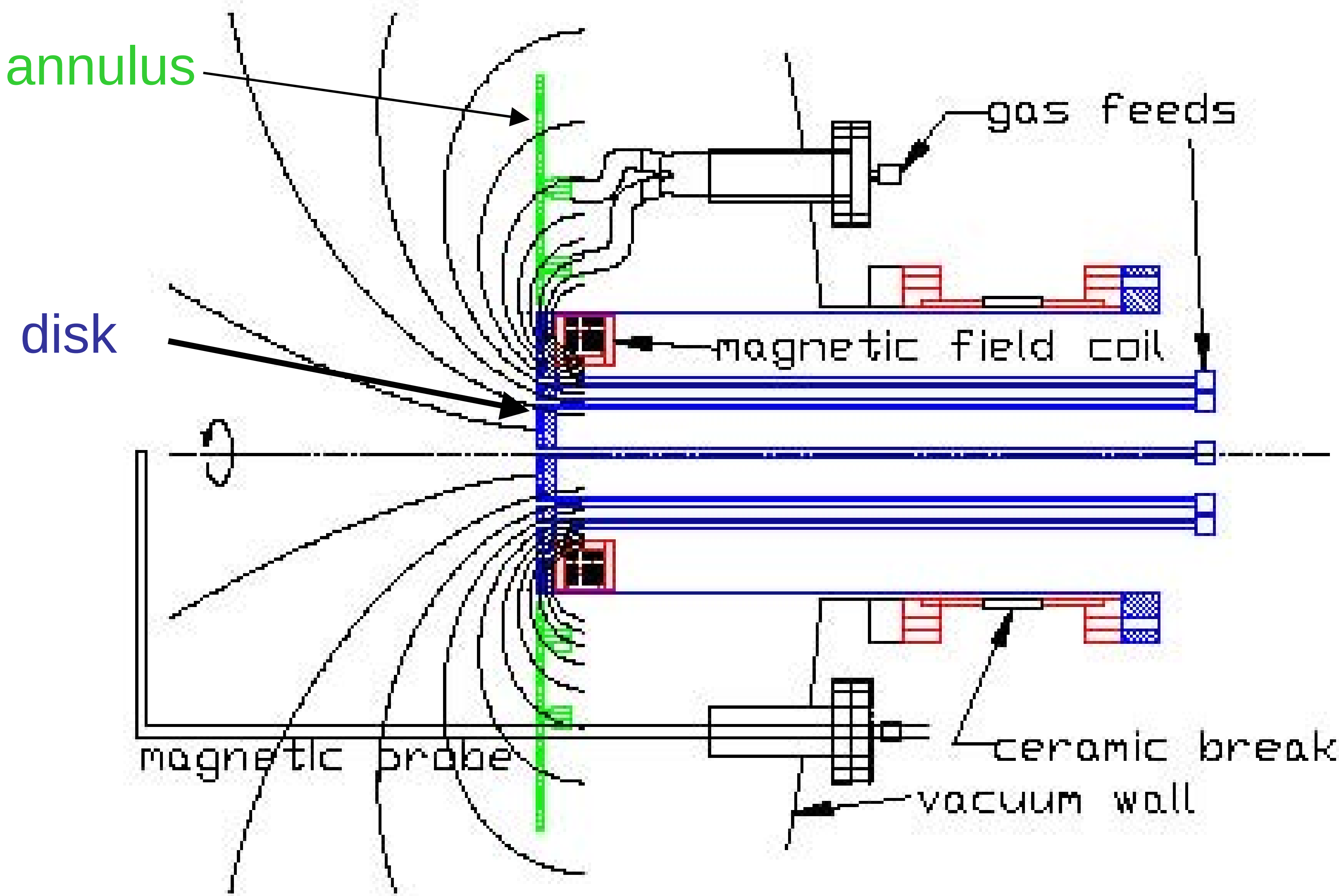
Bias field coil
makes linked
magnetic flux


Gas puff valve
(typical)

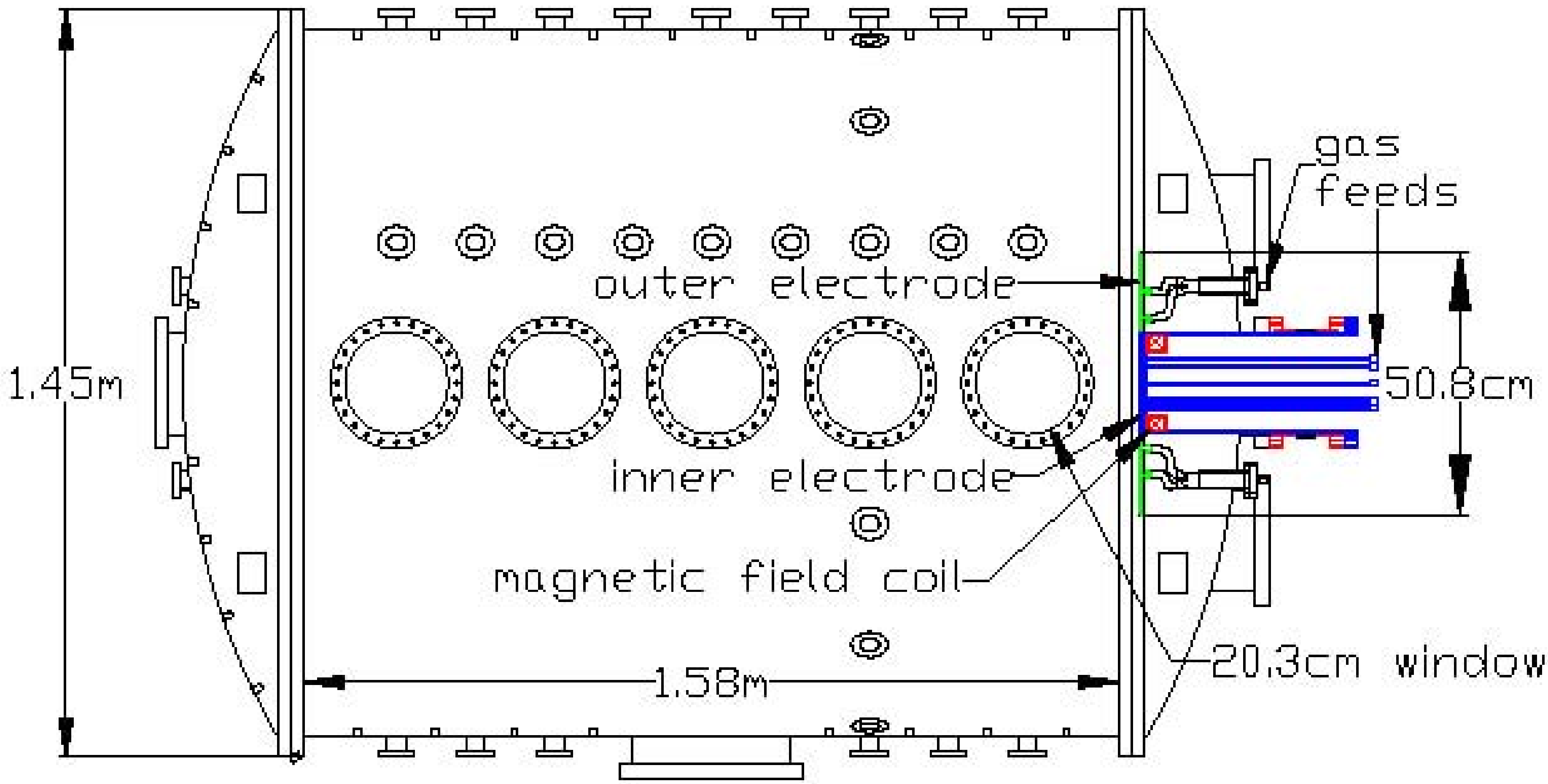


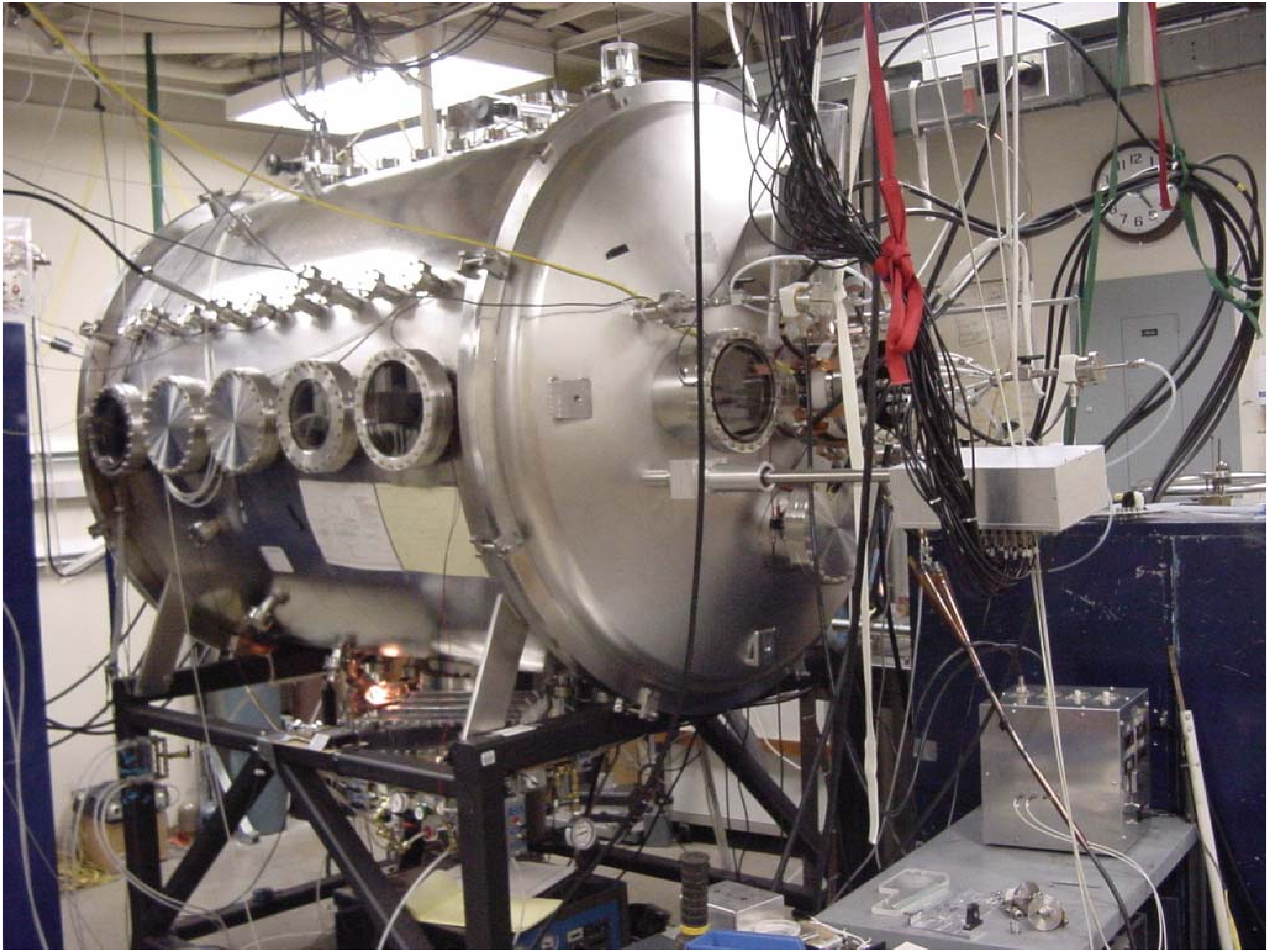

gas nozzles
disk
annulus
50 cm

Side View


annulus
disk
gas feeds
magnetic field coil
ceramic break
magnetic probe
vacuum wall

Installation

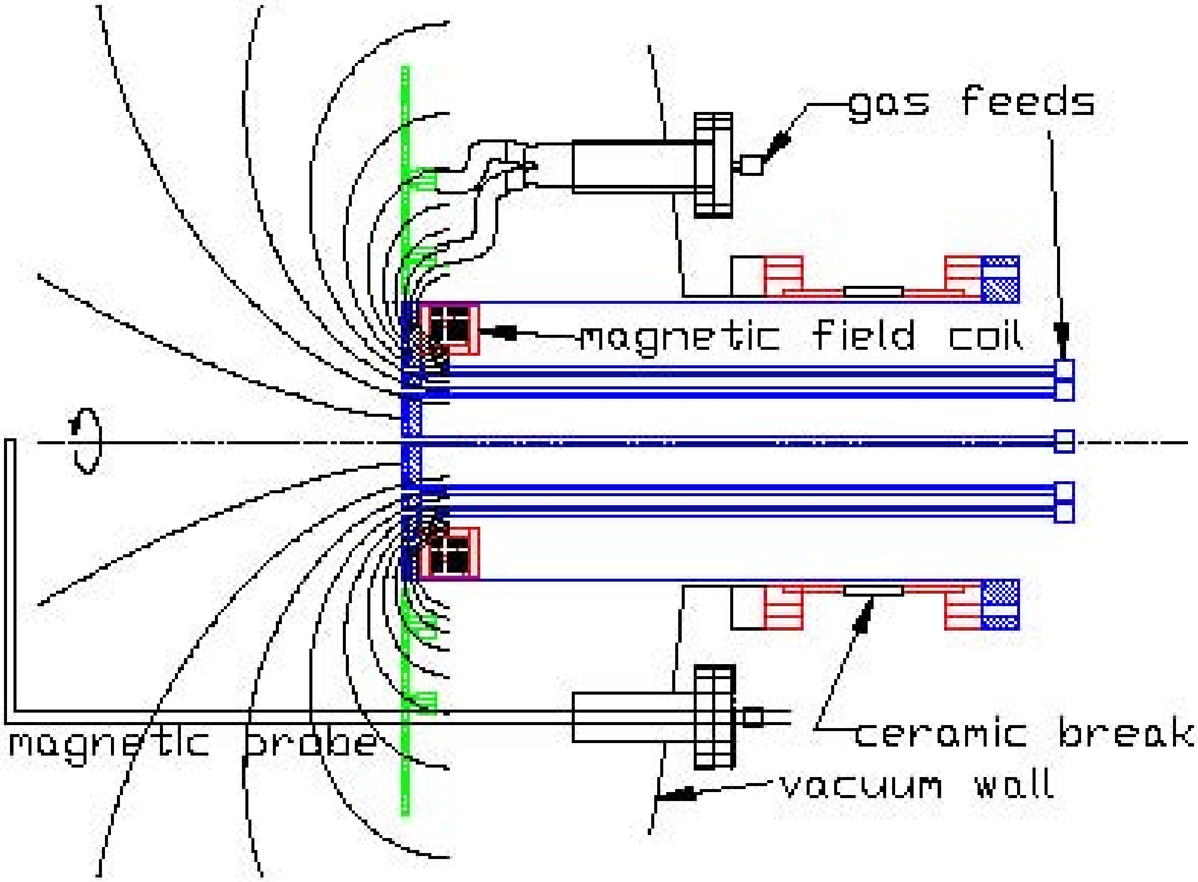




Sequence

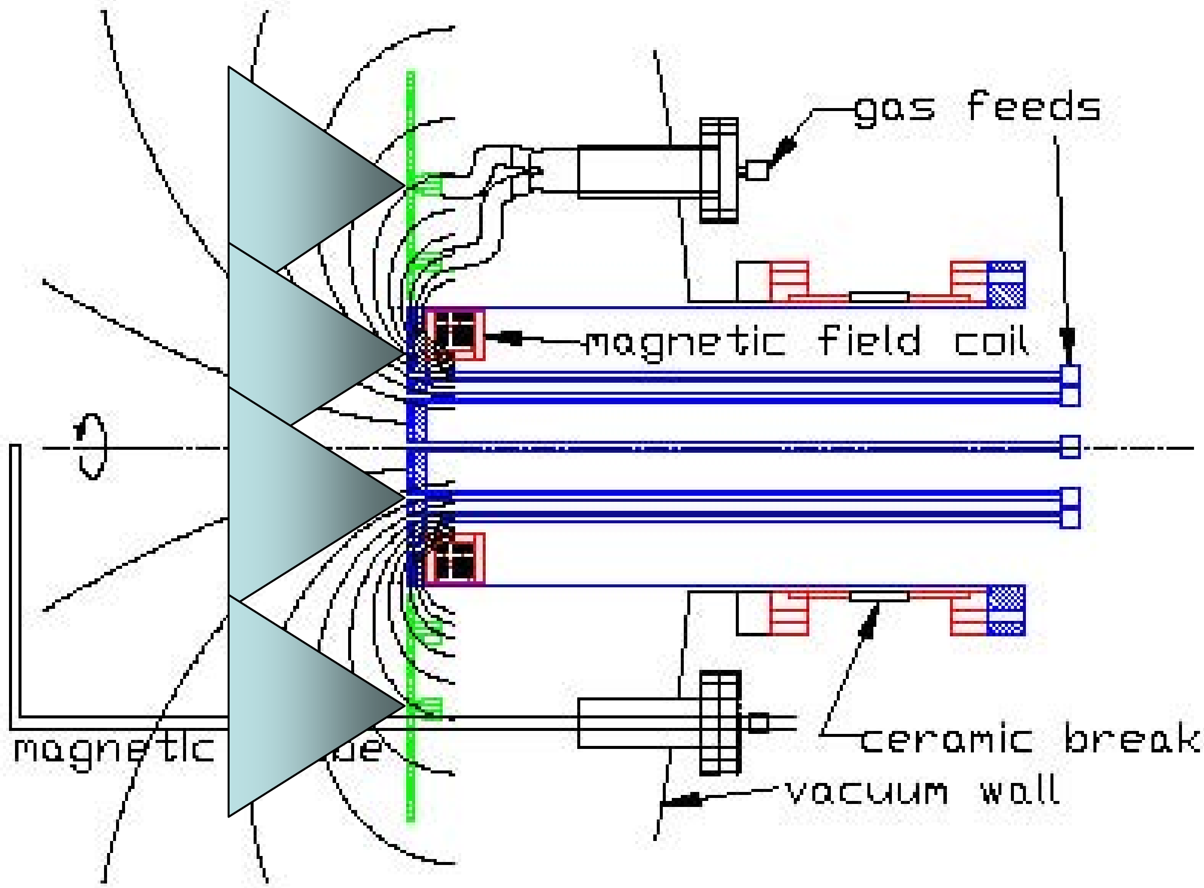
Bias field

high vacuum

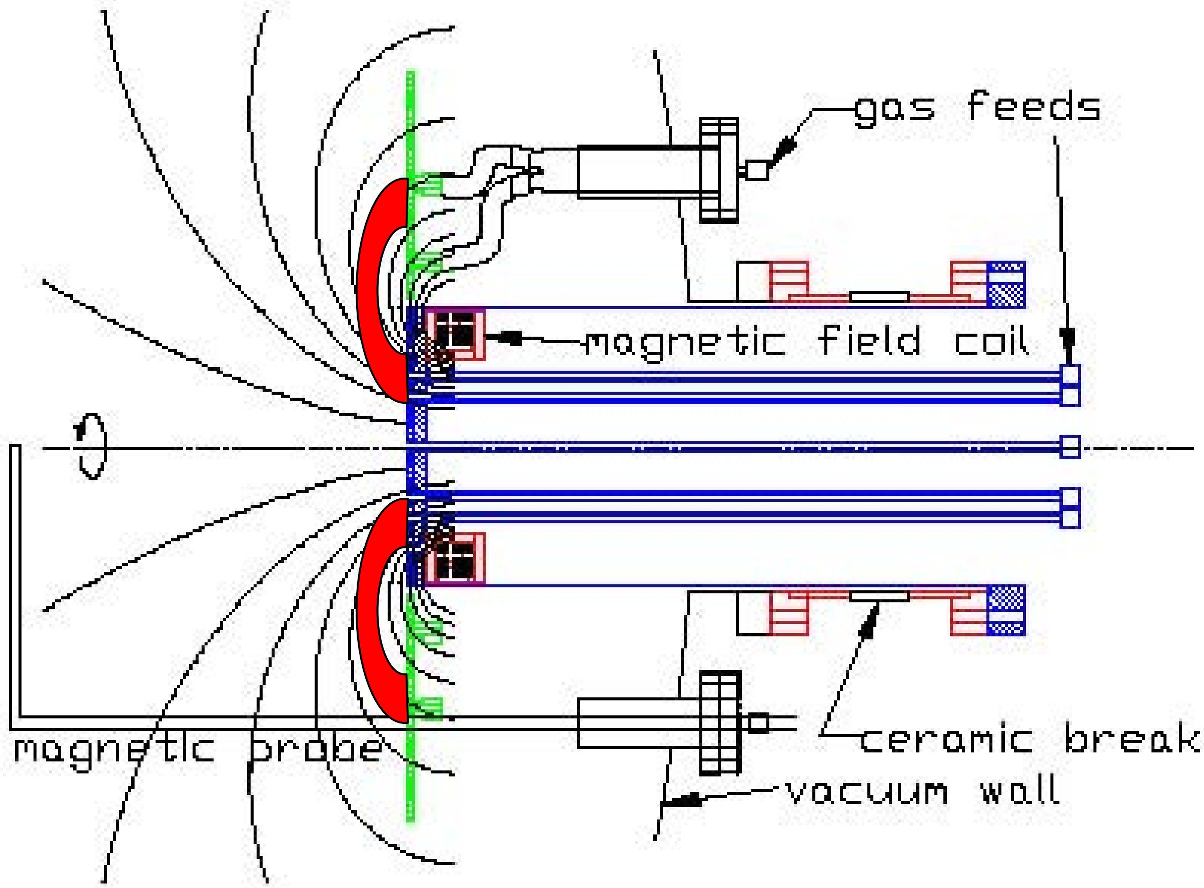


Puff in neutral gas

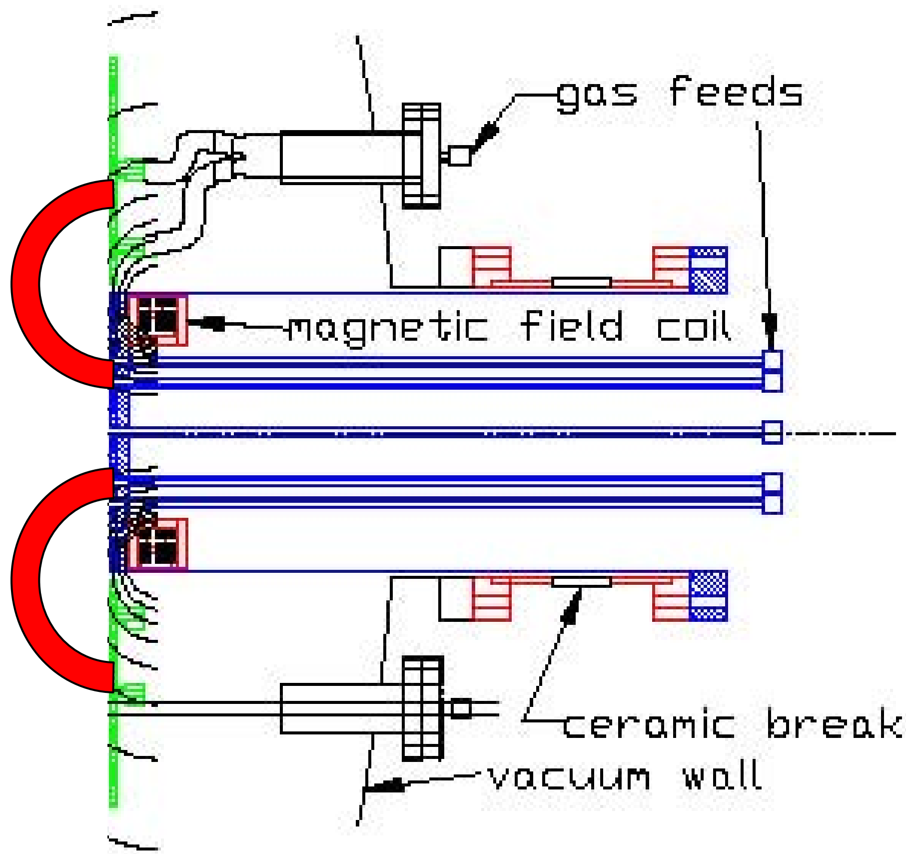
Neutral spatial/temporal profile measured using fast ion gauge probe

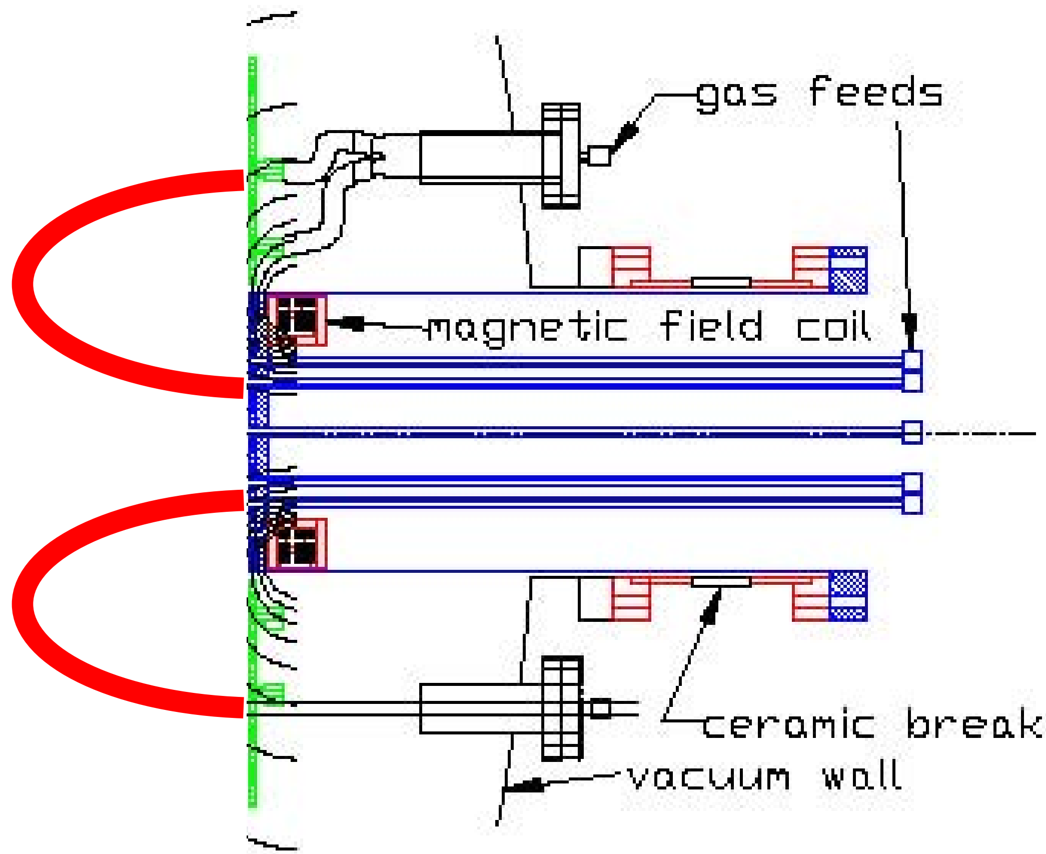


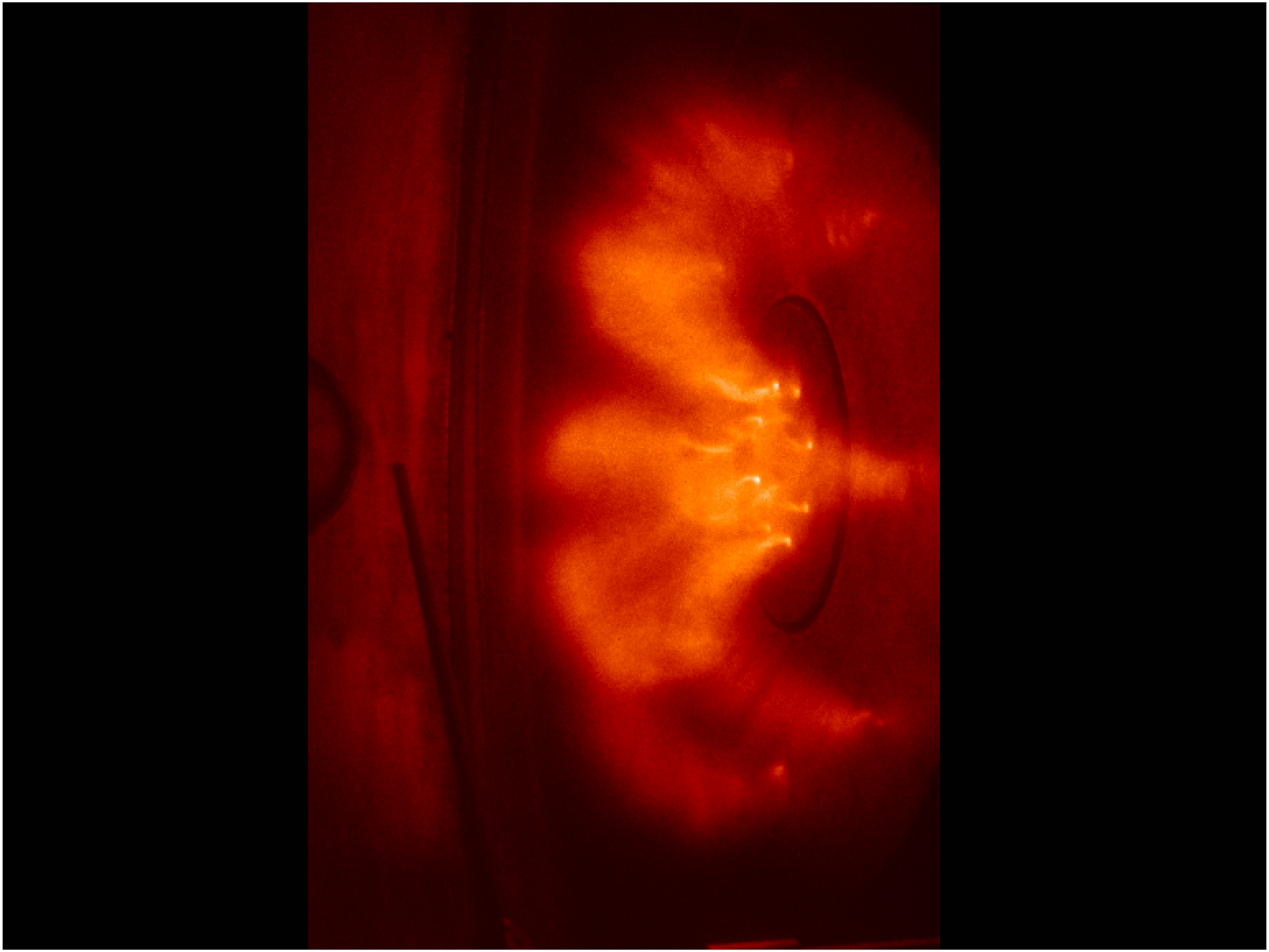
Breakdown, “spider leg formation”



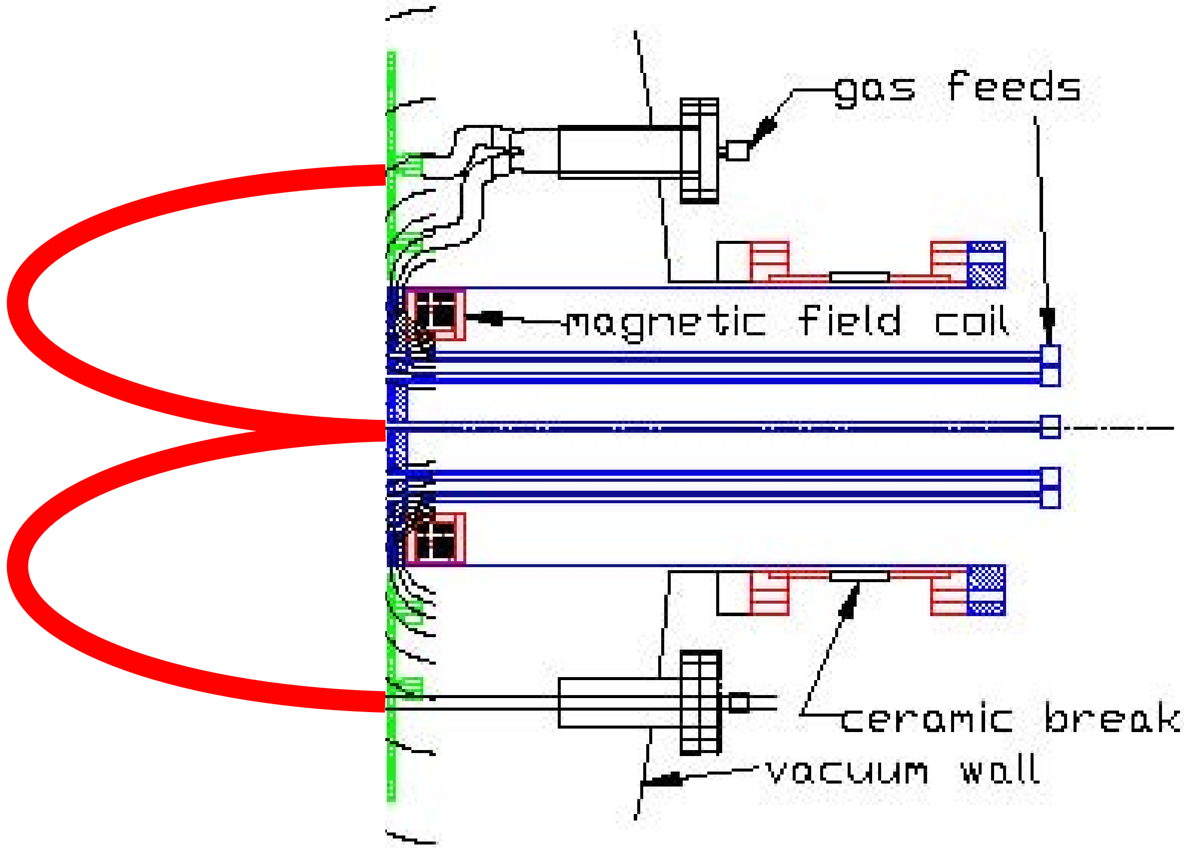
Spider legs get bigger

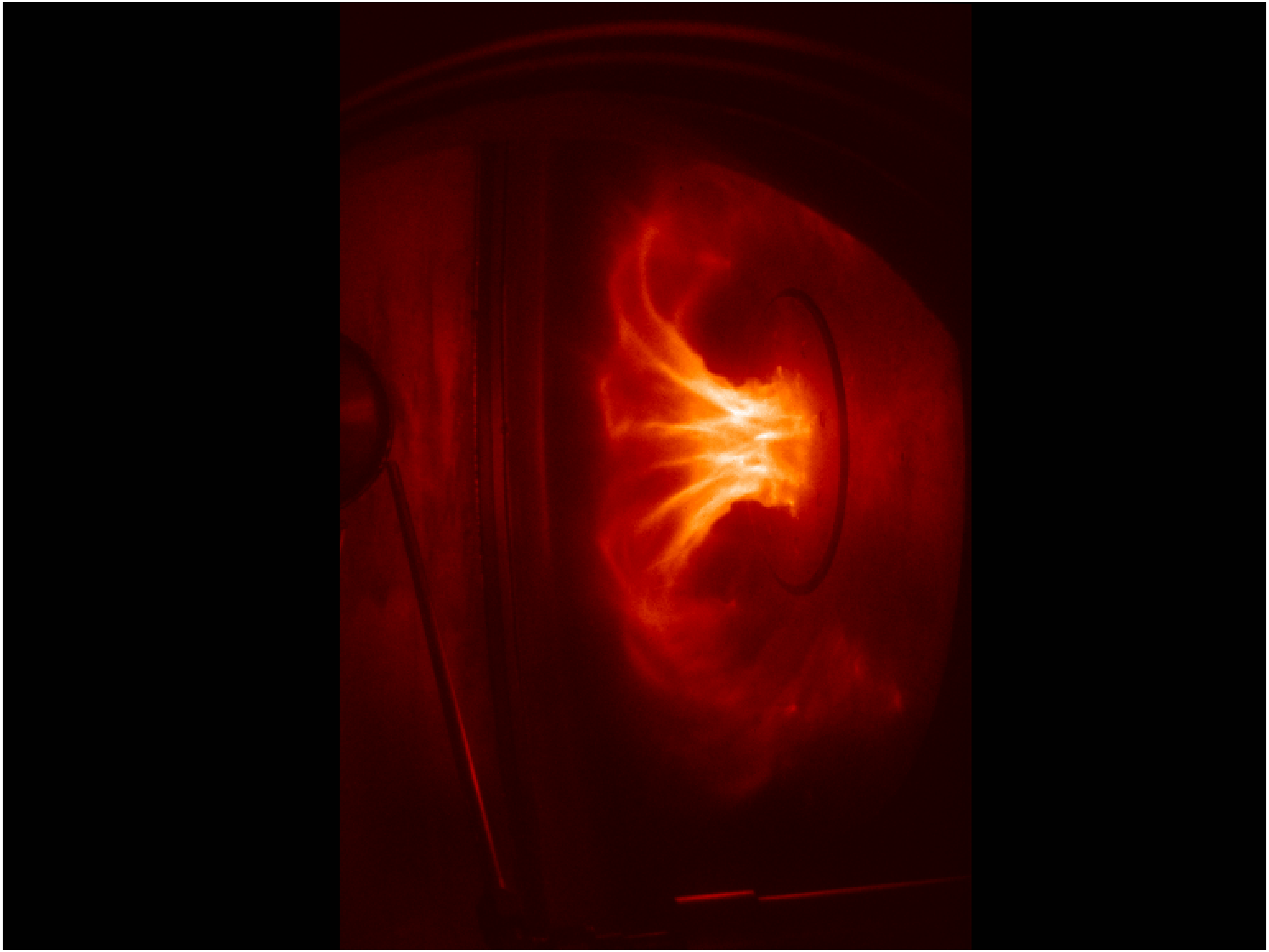



gas feeds
magnetic field coil
ceramic break
vacuum wall

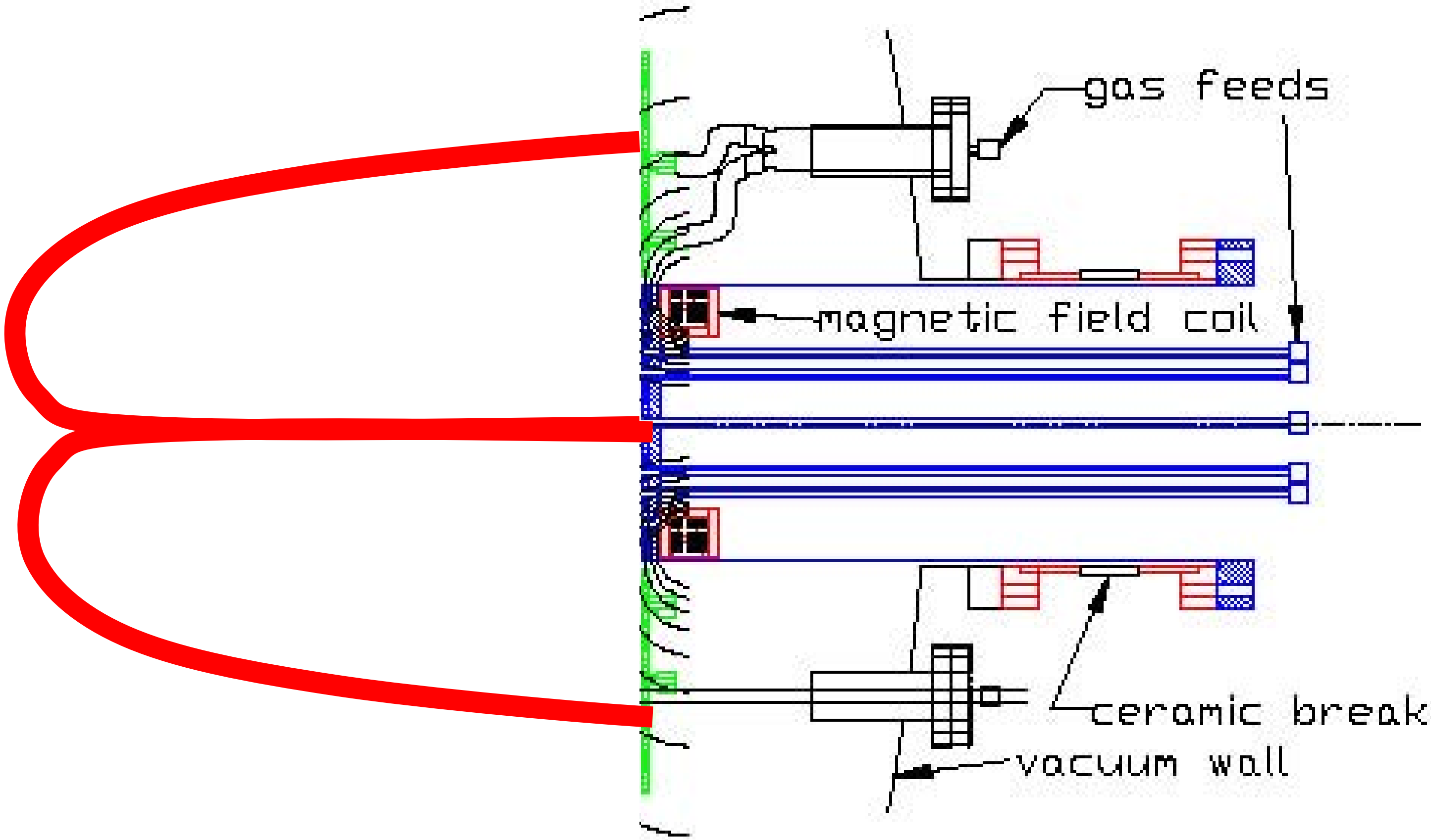


Spider legs merge to form central column

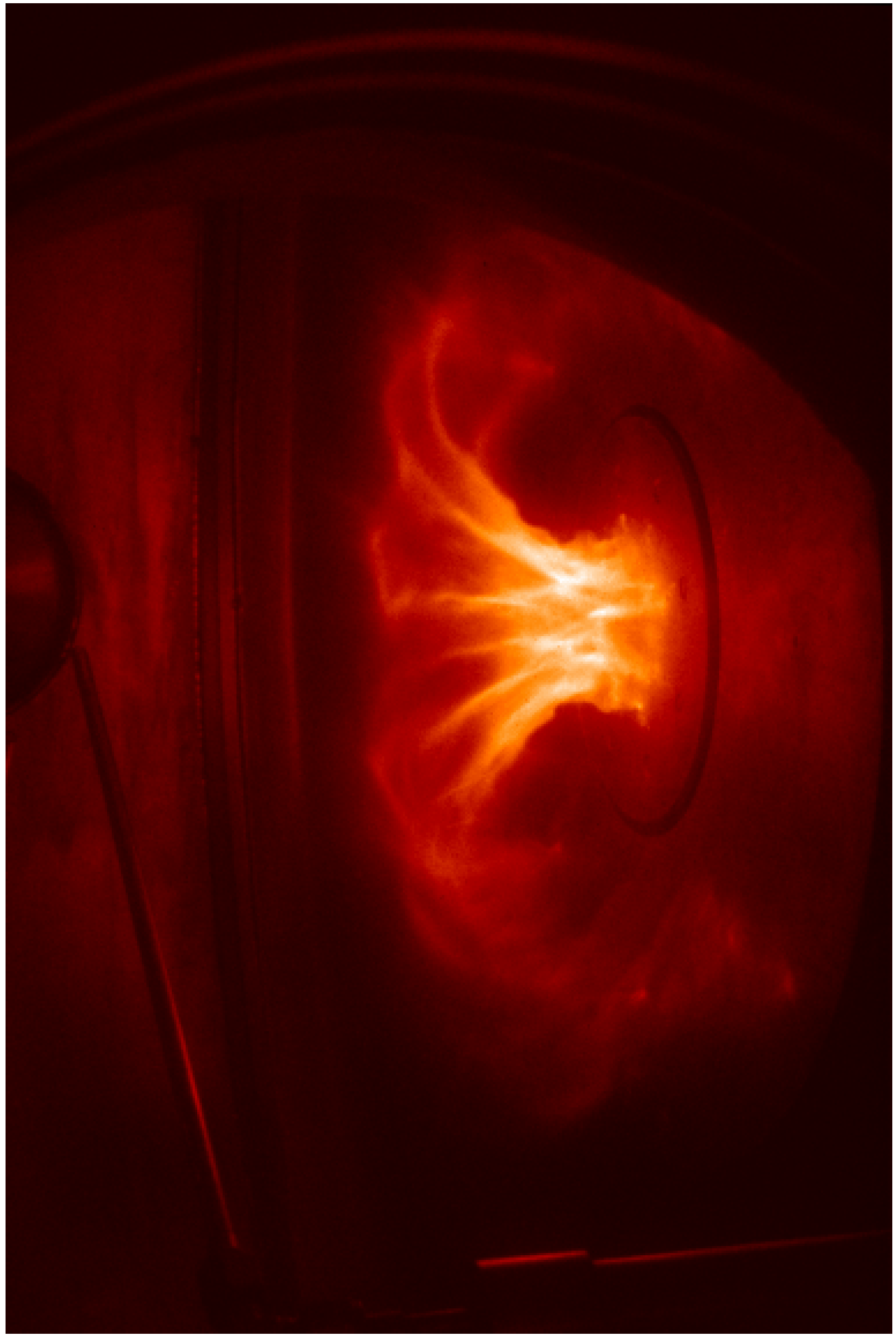


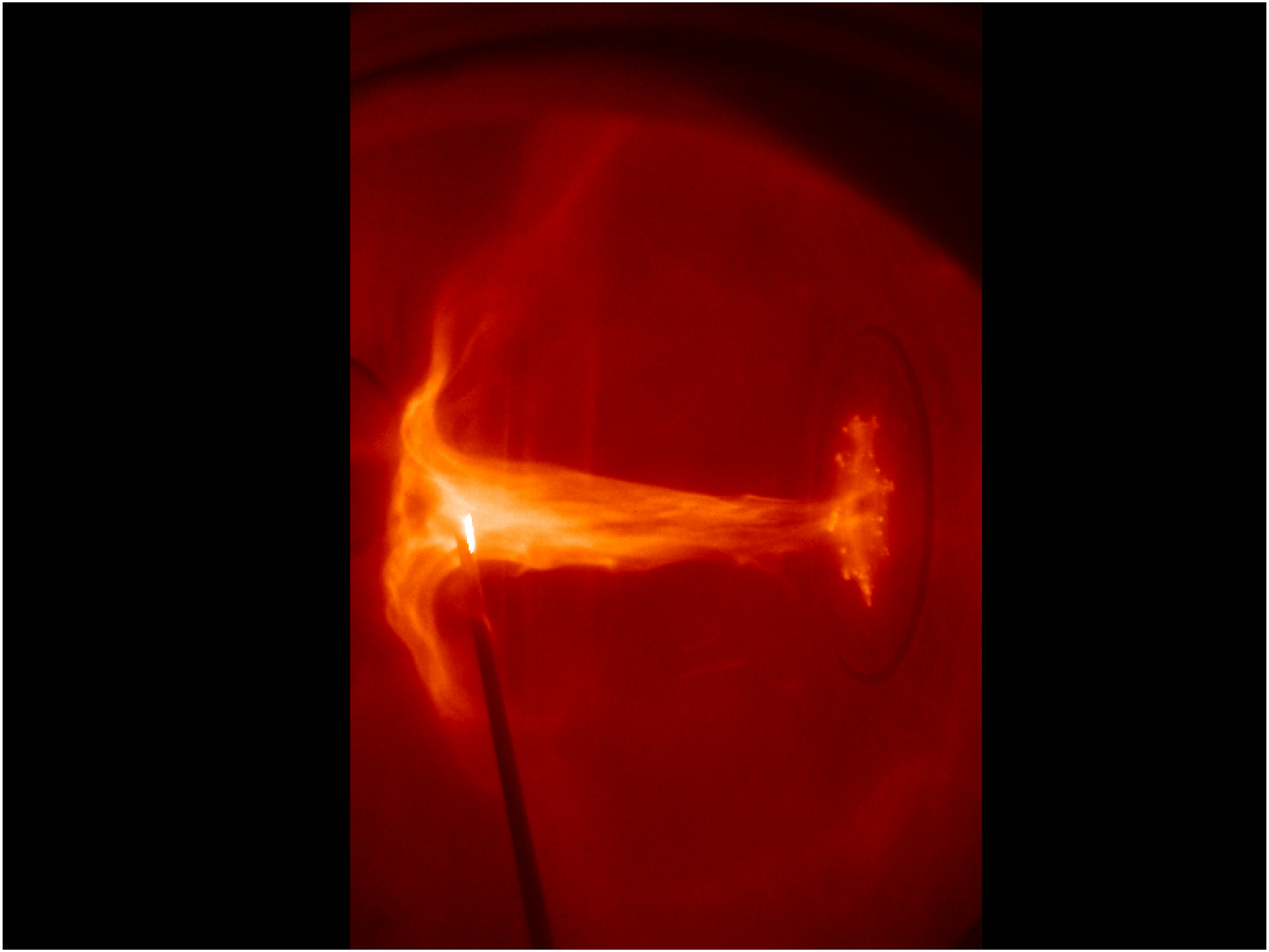


Central column lengthens



I ~ 100 kA

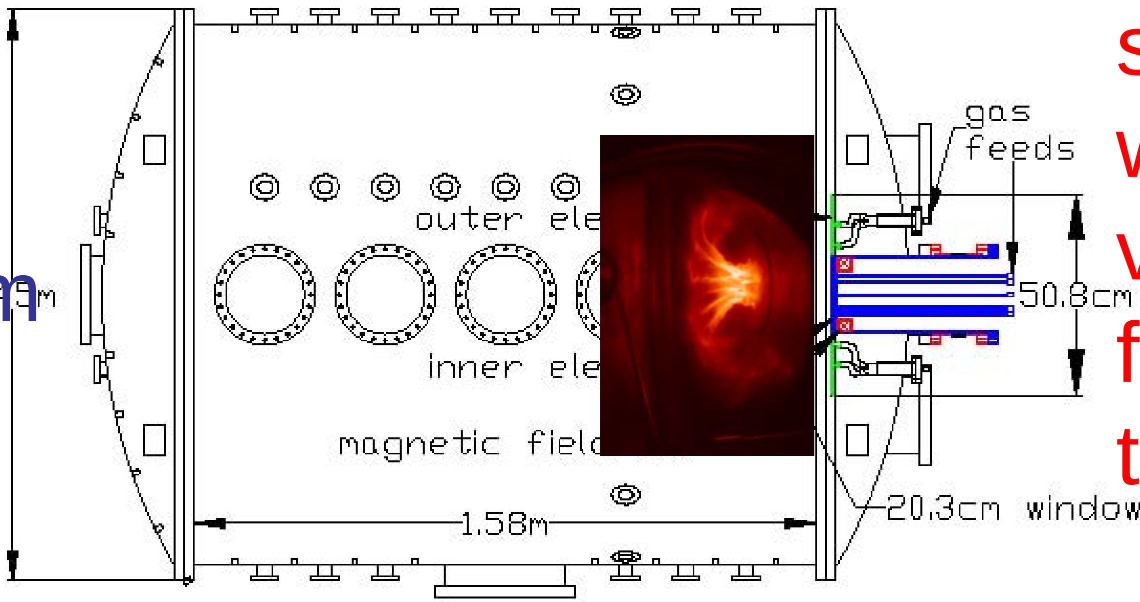




Doppler Shift Measurement

Velocities ~ 15-60 km/s observed

Blue shift seen when viewing from this end



Red shift seen when viewing from this end

Doppler Shift Measurement

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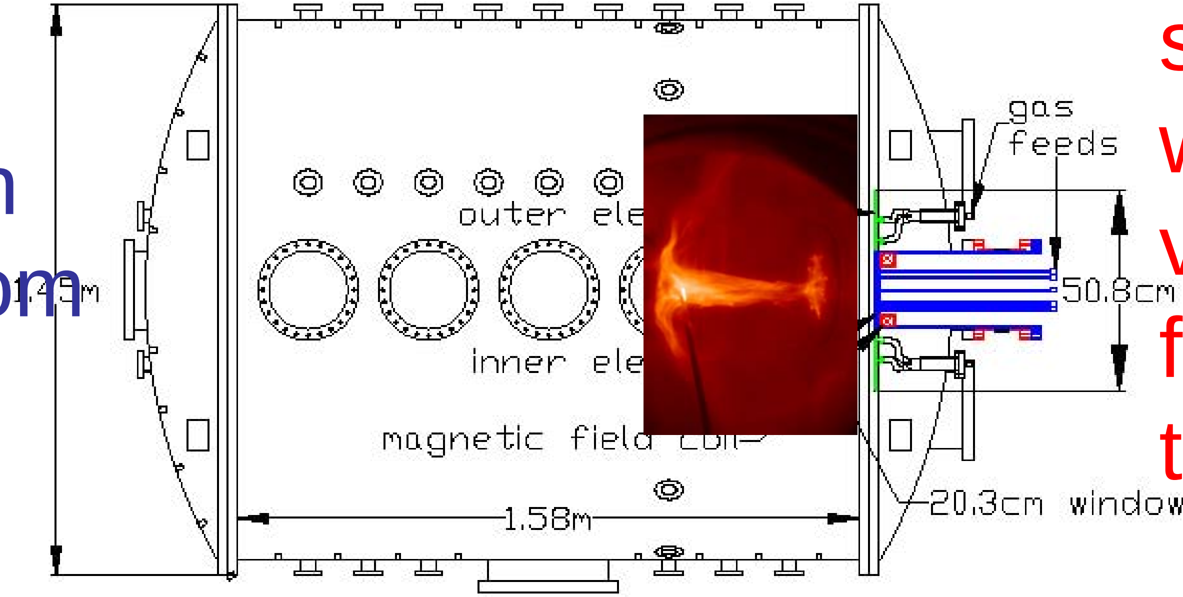
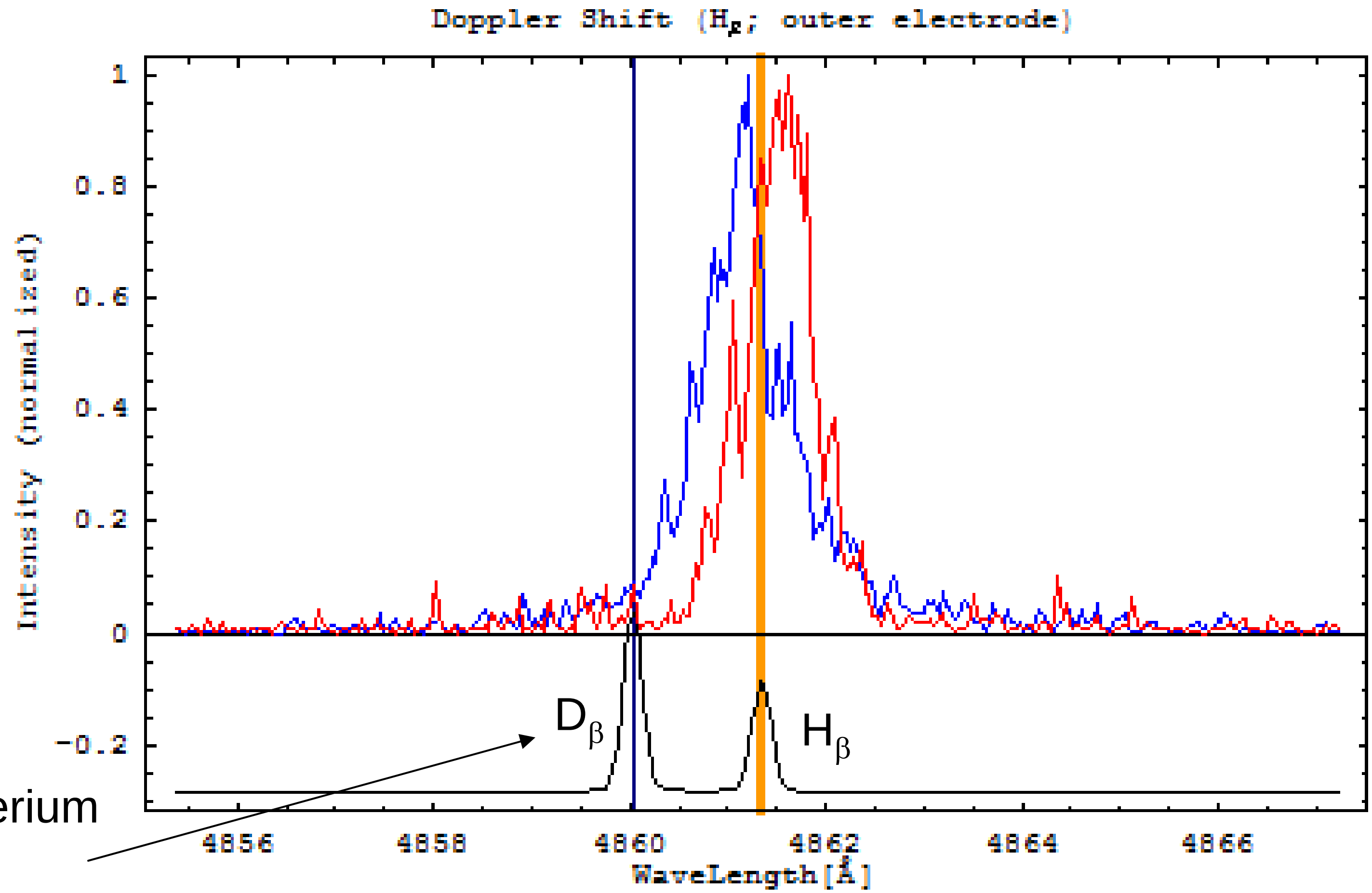


Red shift seen when viewing from this end

Example of Doppler shift data

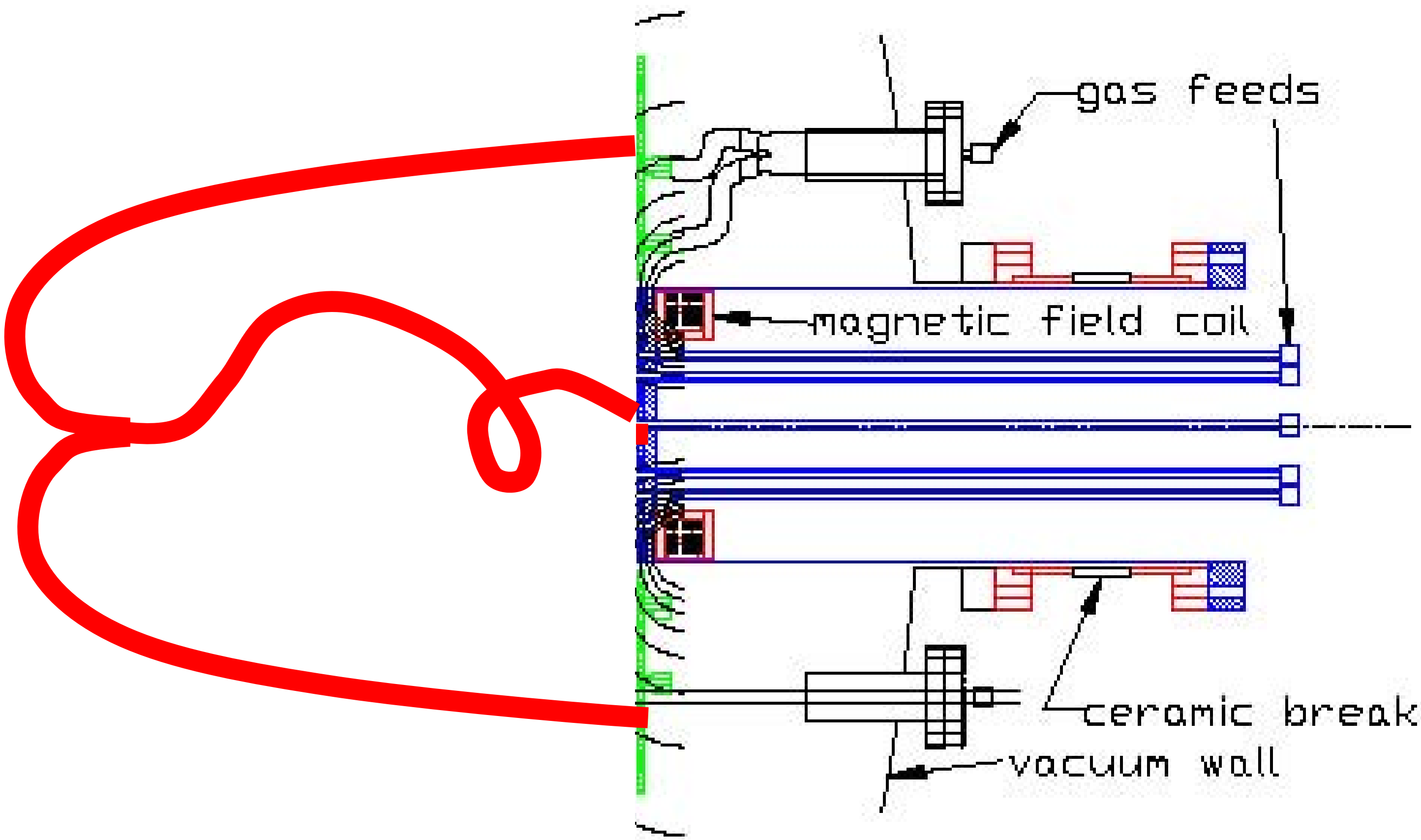


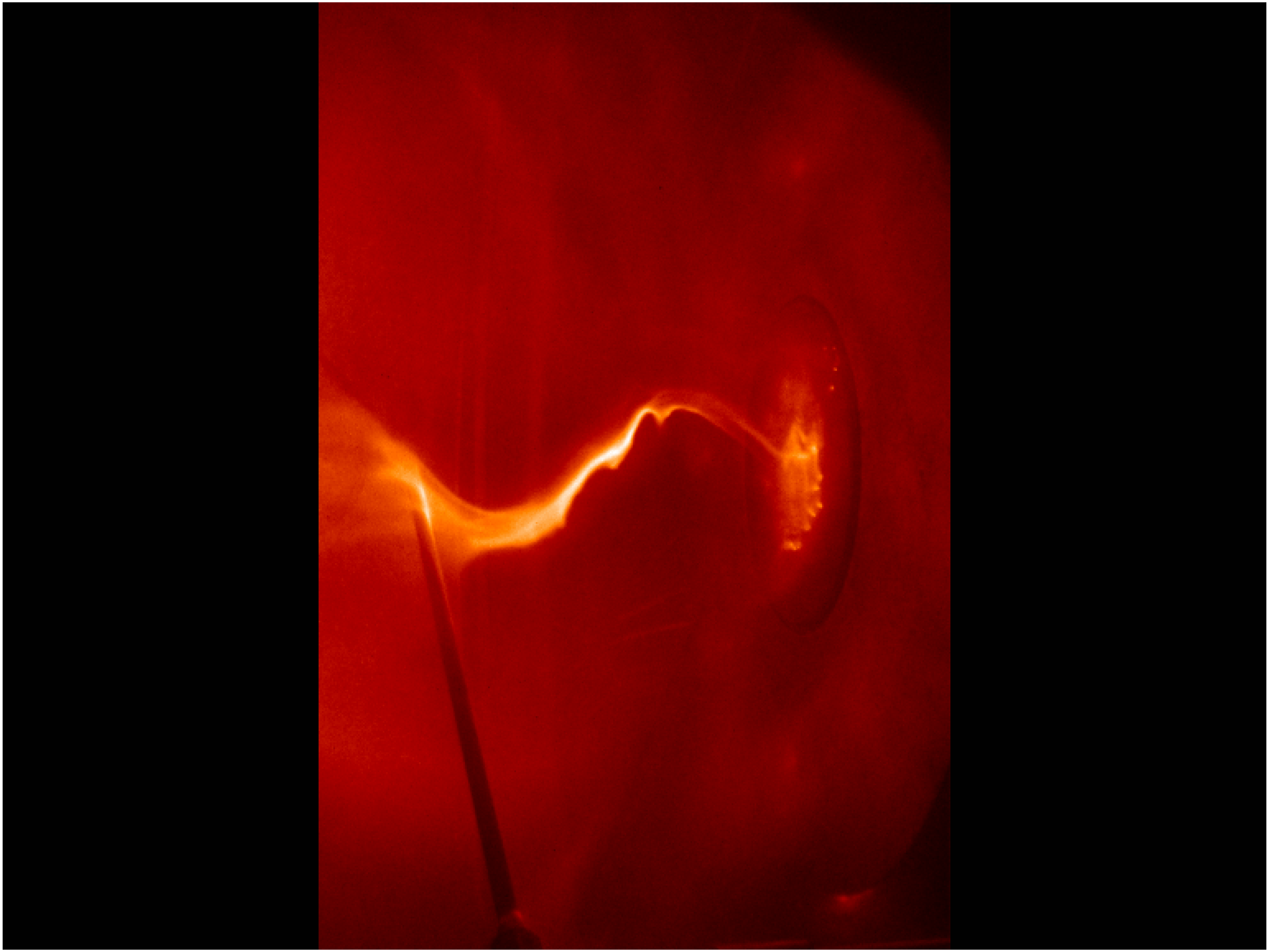
hydrogen, deuterium
calibration lines
from reference lamp

Blue : 4861.15 ⟹ -11.3339 [km/s] (blue shift)

Red : 4861.54 ⟹ 13.165 [km/s] (red shift)

Kink Instability of Central Column



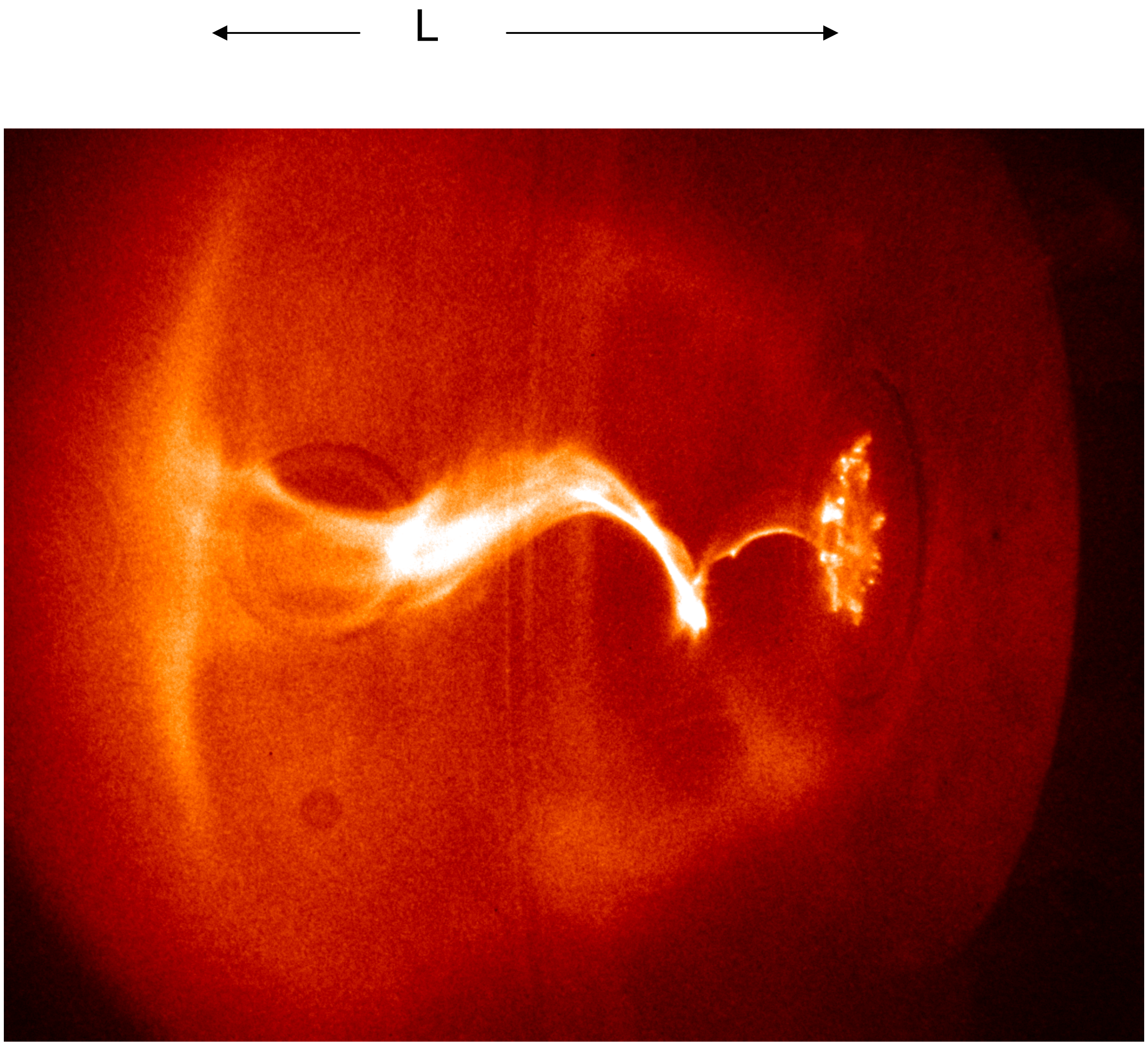


Kink instability of central column, cont'd

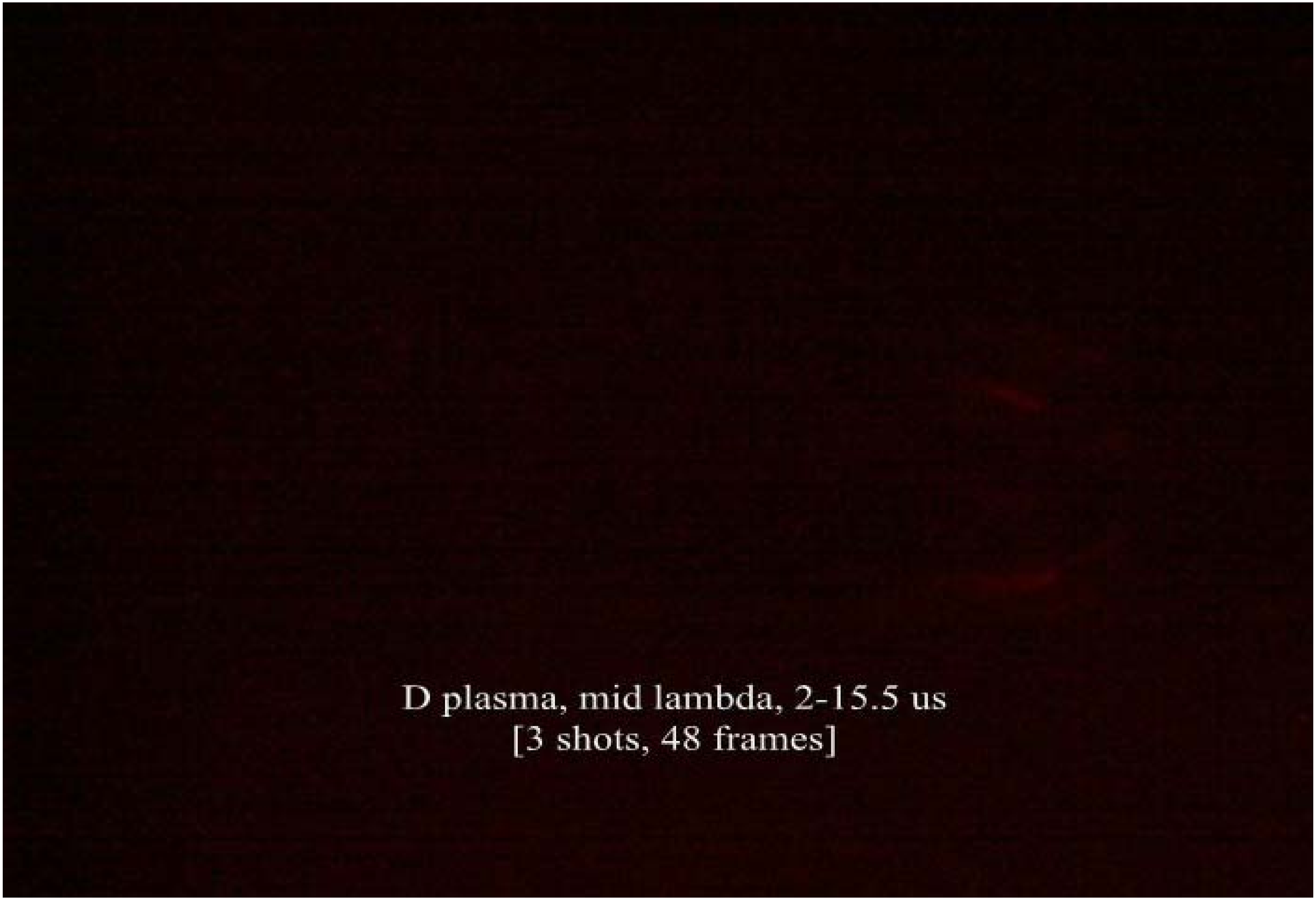
Kink occurs when central column becomes sufficiently long to satisfy Kruskal-Shafranov instability condition

$$q = \frac{2\pi R}{L}\frac{B_\phi}{B_z}$$

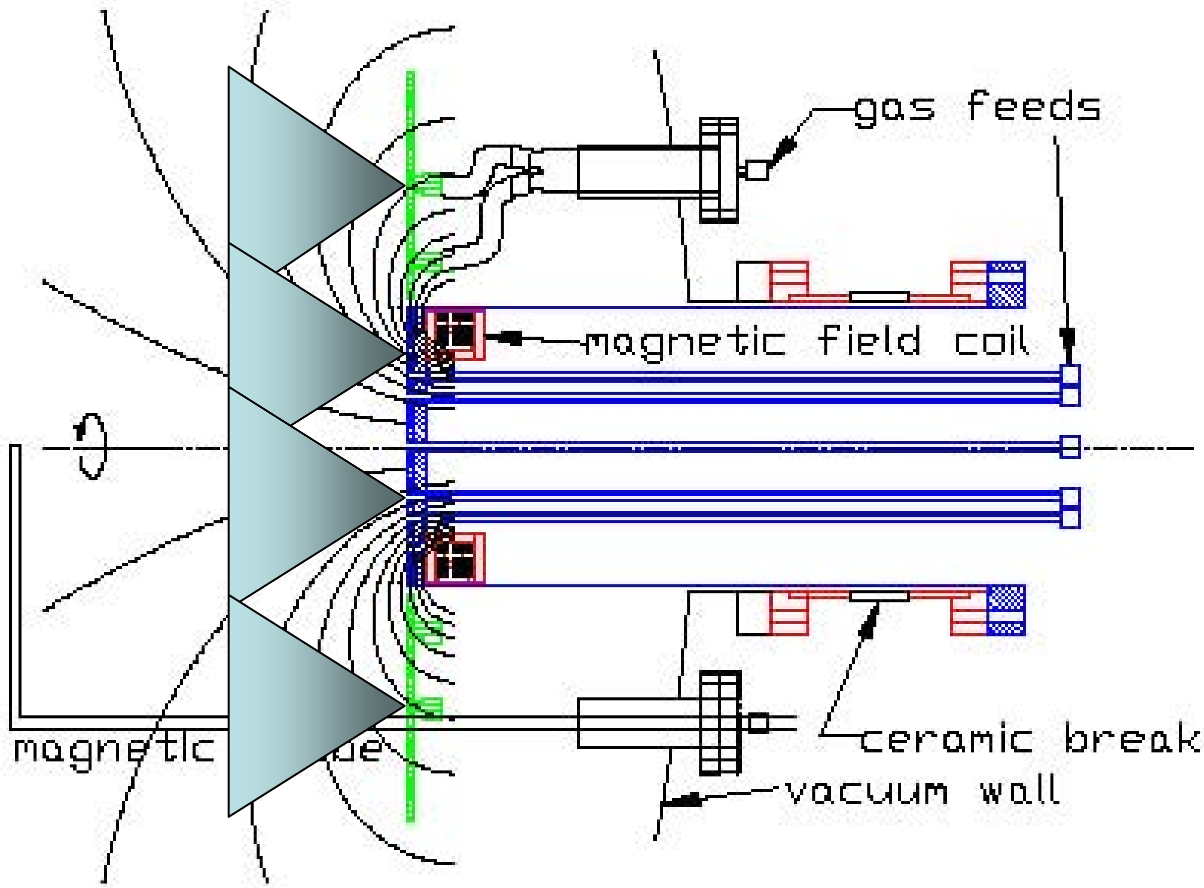
S. C. Hsu & P. M. Bellan
MNRAS 334, 257 (2002)



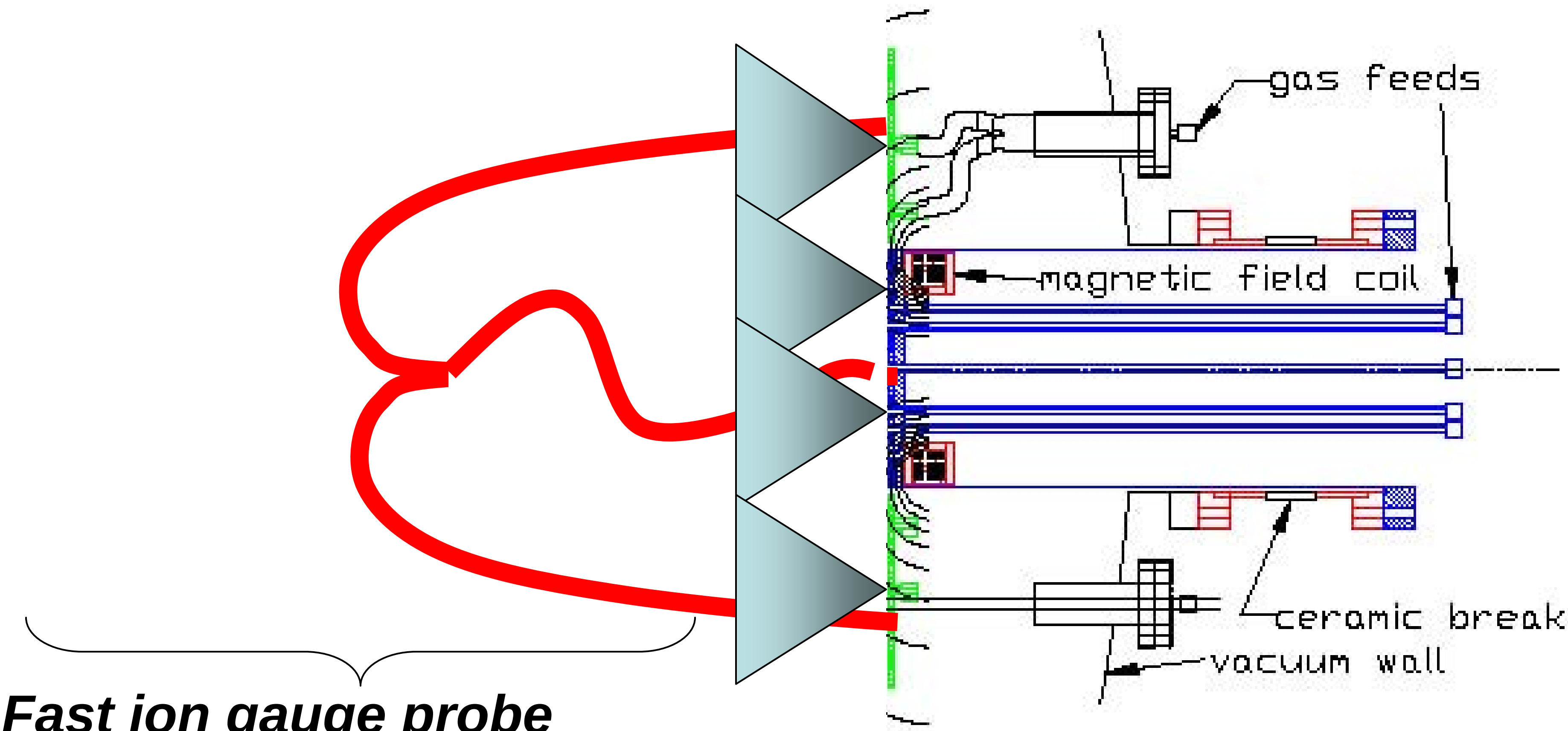
movie showing collimated jet and kink instability


D plasma, mid lambda, 2-15.5 us
[3 shots, 48 frames]

Neutral density profile <u>measured absolutely</u> using <u>calibrated fast ion gauge probe</u>

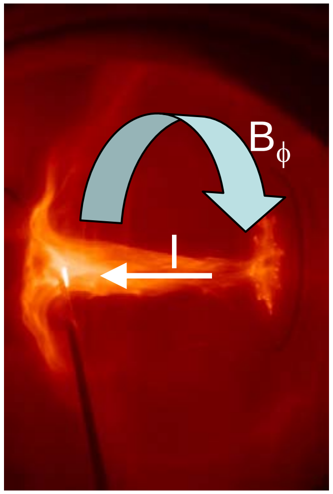


Question:
Where does plasma come from?



Fast ion gauge probe shows there is no gas here initially, i.e., near vacuum

Toroidal flux injection



- gun current creates toroidal flux

- voltage across electrodes = rate at which toroidal flux is injected
  - coil creates poloidal flux Ψ linking toroidal flux
  - helicity injection rate $=2V\Psi$

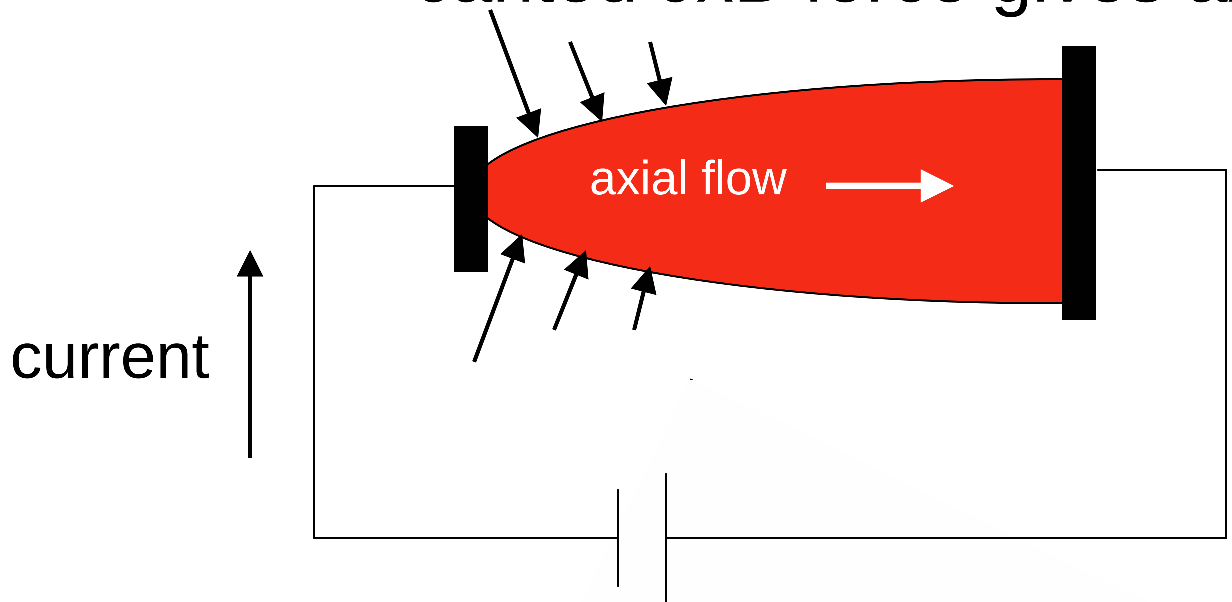
Mass influx

- toroidal flux is frozen into plasma
  - **toroidal flux injection implies there must be plasma injection also**
  - this is the key concept
- need source of plasma: gas nozzle is the source for ingested plasma
- gas source properties control magnetic properties

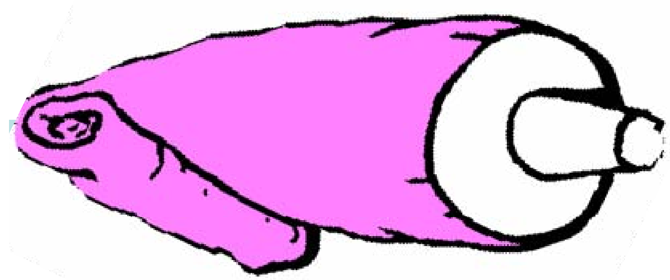
Collimation

- Plasma and toroidal flux frozen together
- Pile-up (traffic jam) of ingested plasma corresponds to a converging flow, compression
- Embedded toroidal flux is also compressed, strengthening toroidal magnetic field
- This causes collimation ($I \sim rB_\phi$=constant)
- Very high densities in a filamentary flux tube (substantial Stark broadening observed)

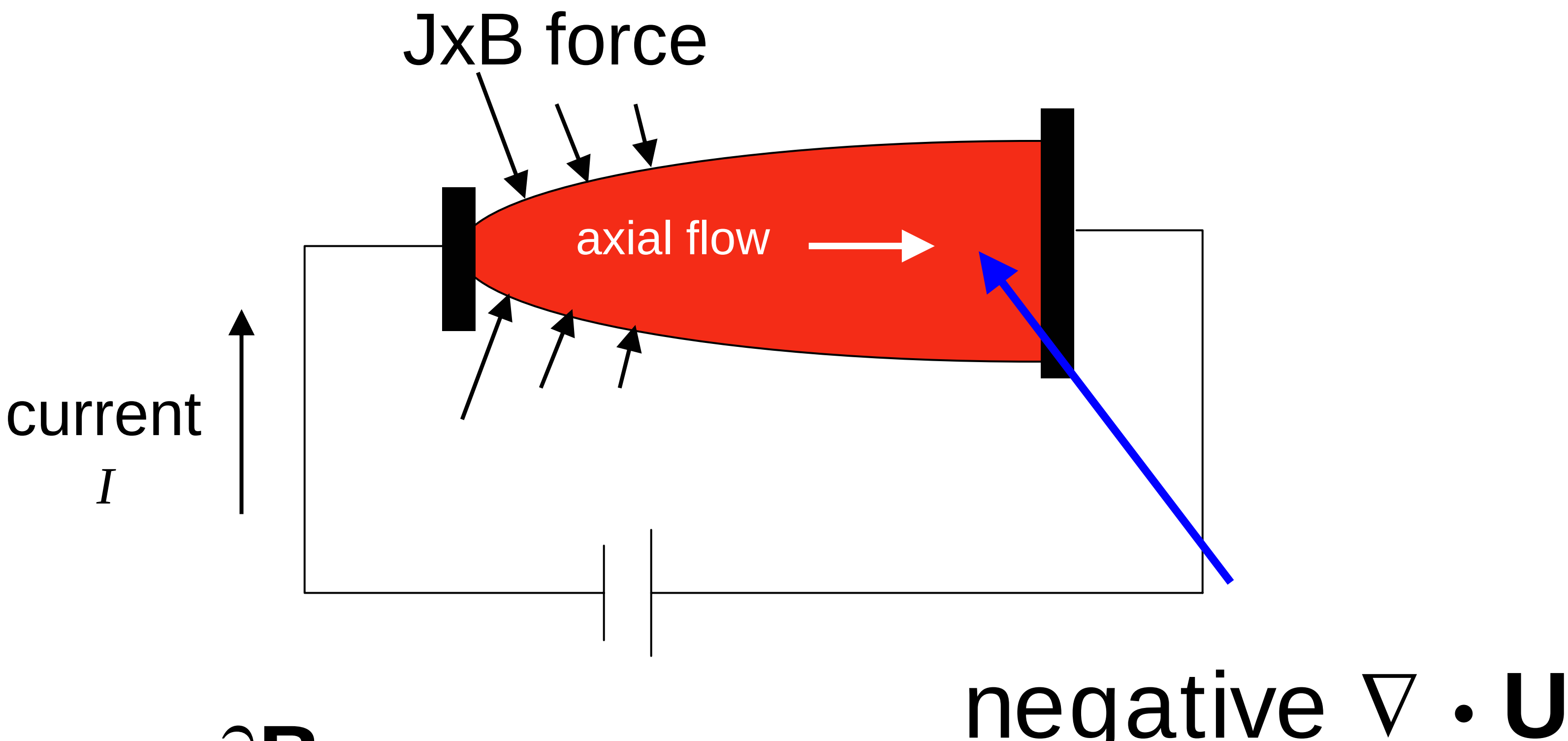
canted JxB force gives axial thrust



Like squirting toothpaste from a toothpaste tube



Jet flow and collimation



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B})$$

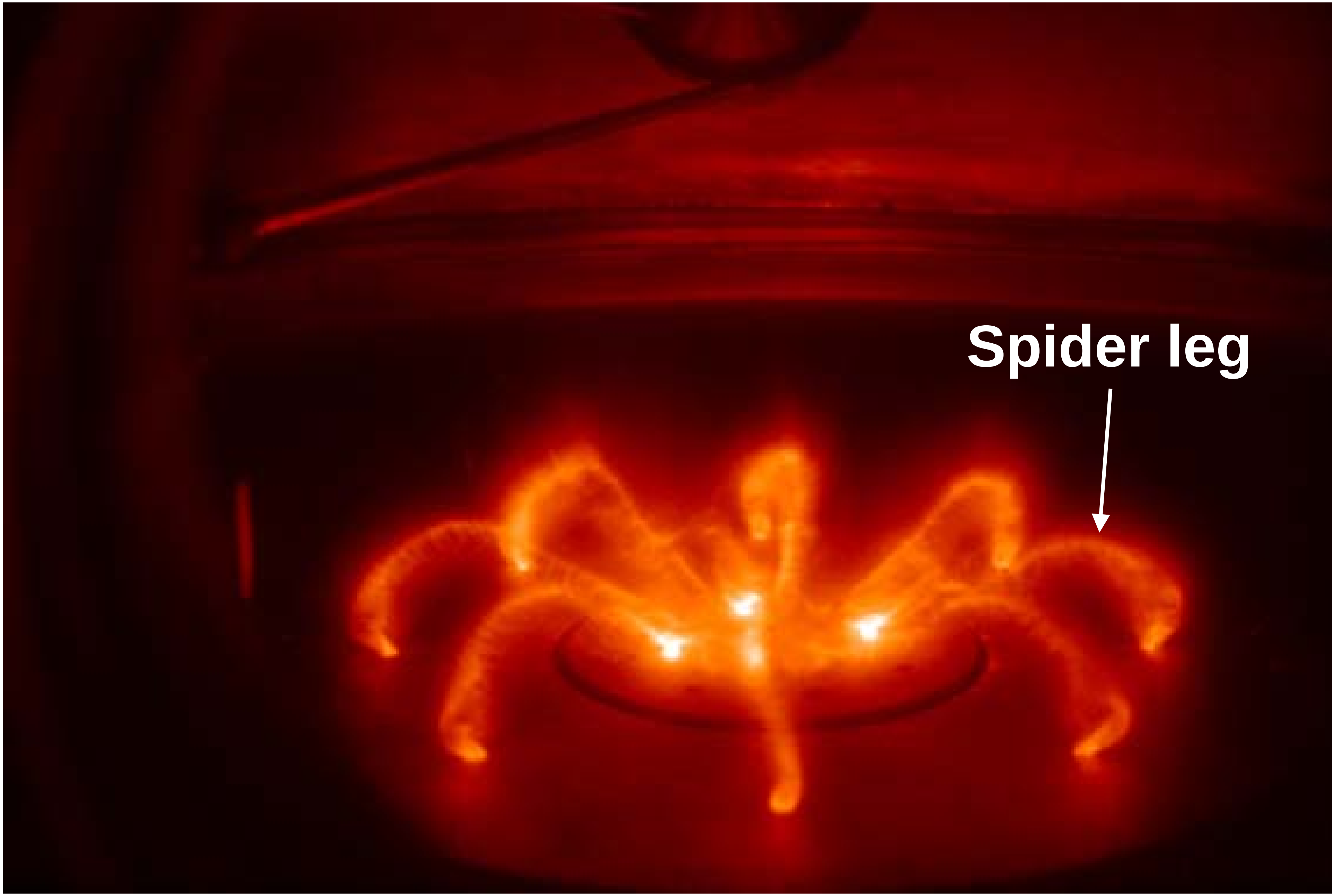
$$\Rightarrow \frac{d\mathbf{B}}{dt} = \mathbf{B} \cdot \nabla \mathbf{U} - \mathbf{B} \nabla \cdot \mathbf{U}$$

$B_{azimuthal}$ amplification

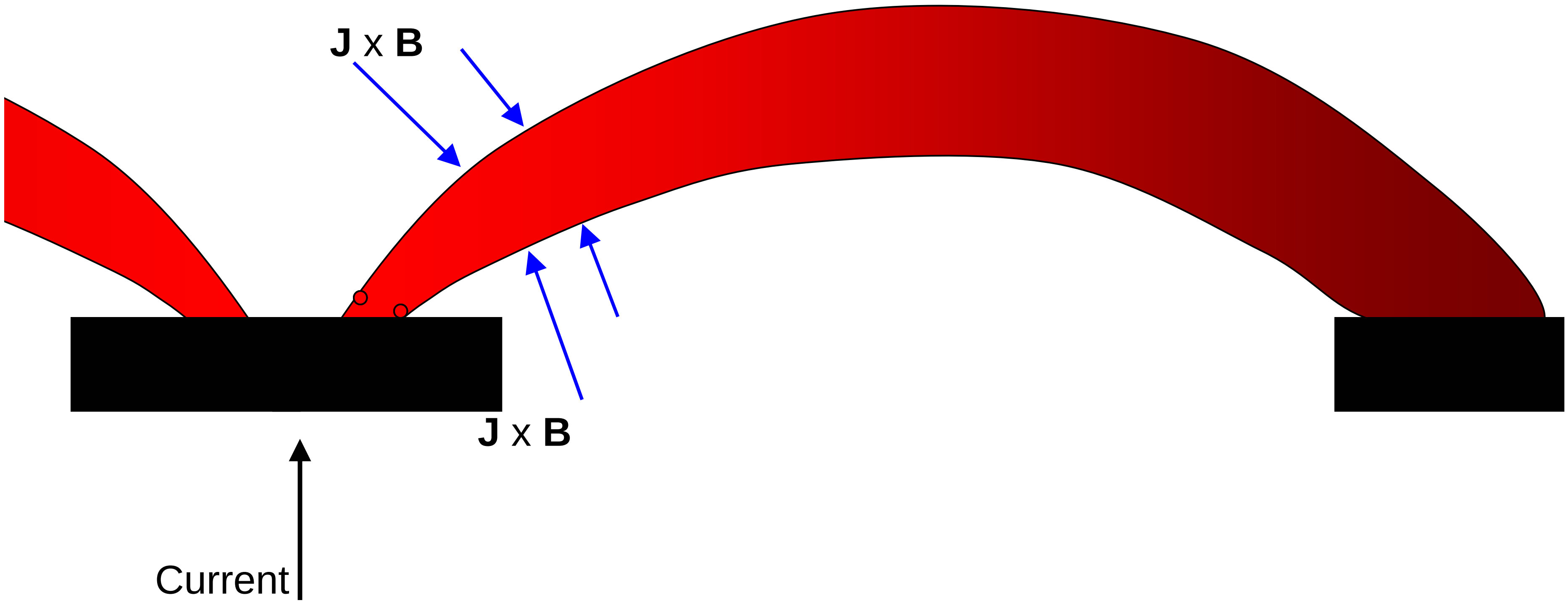
$\Rightarrow$ r decrease to keep $\mu_0 I = 2\pi r B_{azimuthal}$ constant

Spider leg evolution

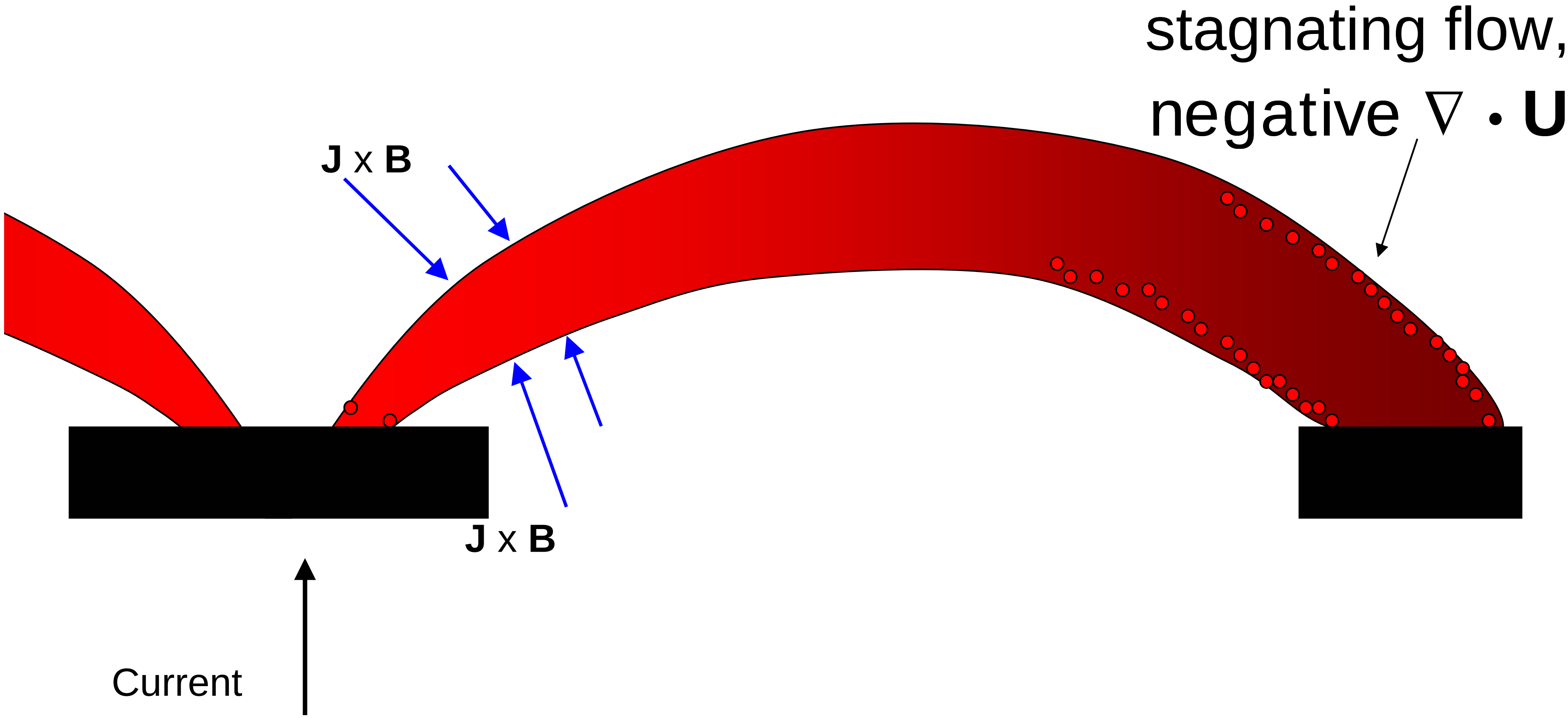
- At breakdown see plasma jets coming from gas valves on central disk
- Jets stagnate, spider leg becomes collimated
- Dense, hot plasma in collimated spider leg


Spider leg

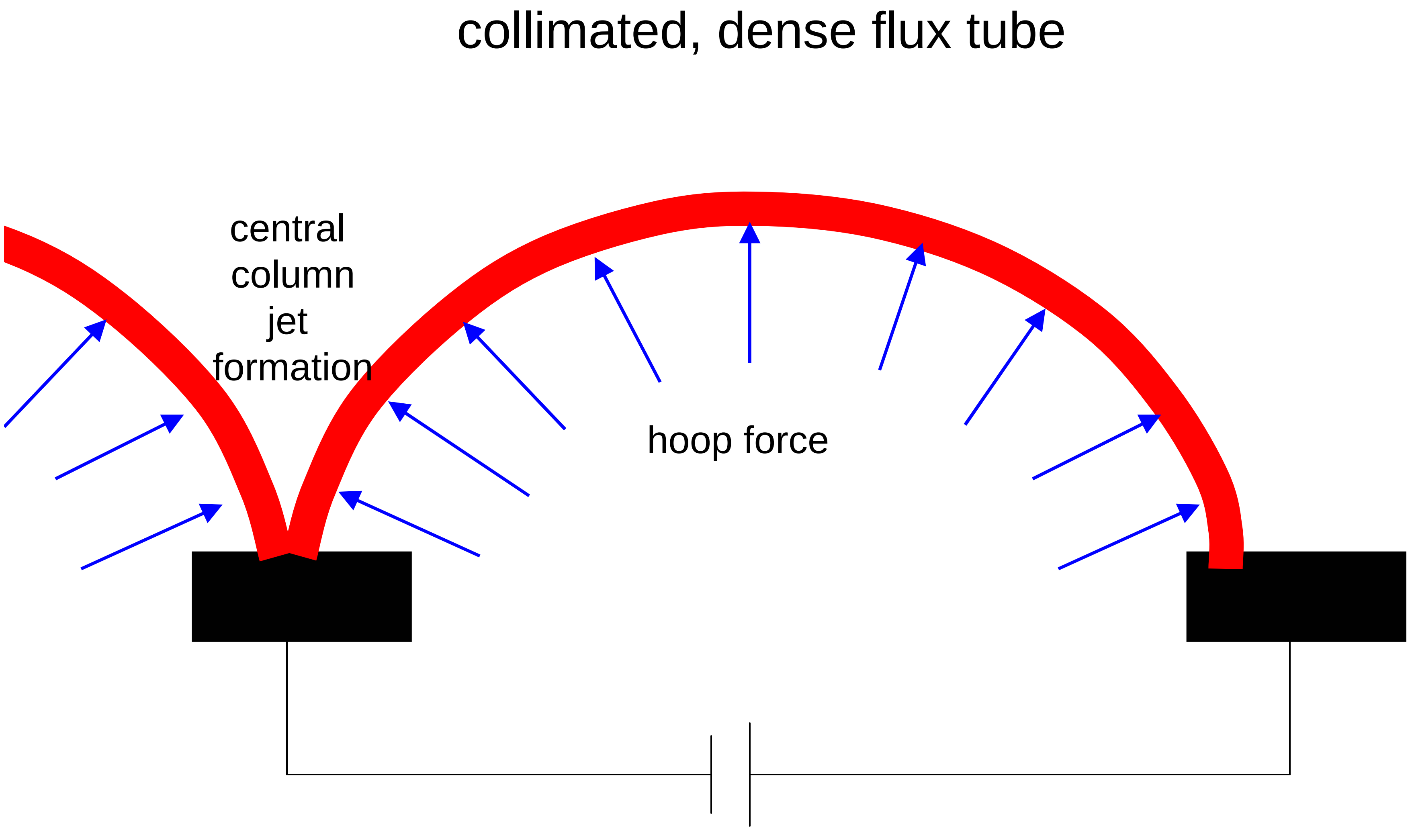
Spider leg evolution



Spider leg evolution

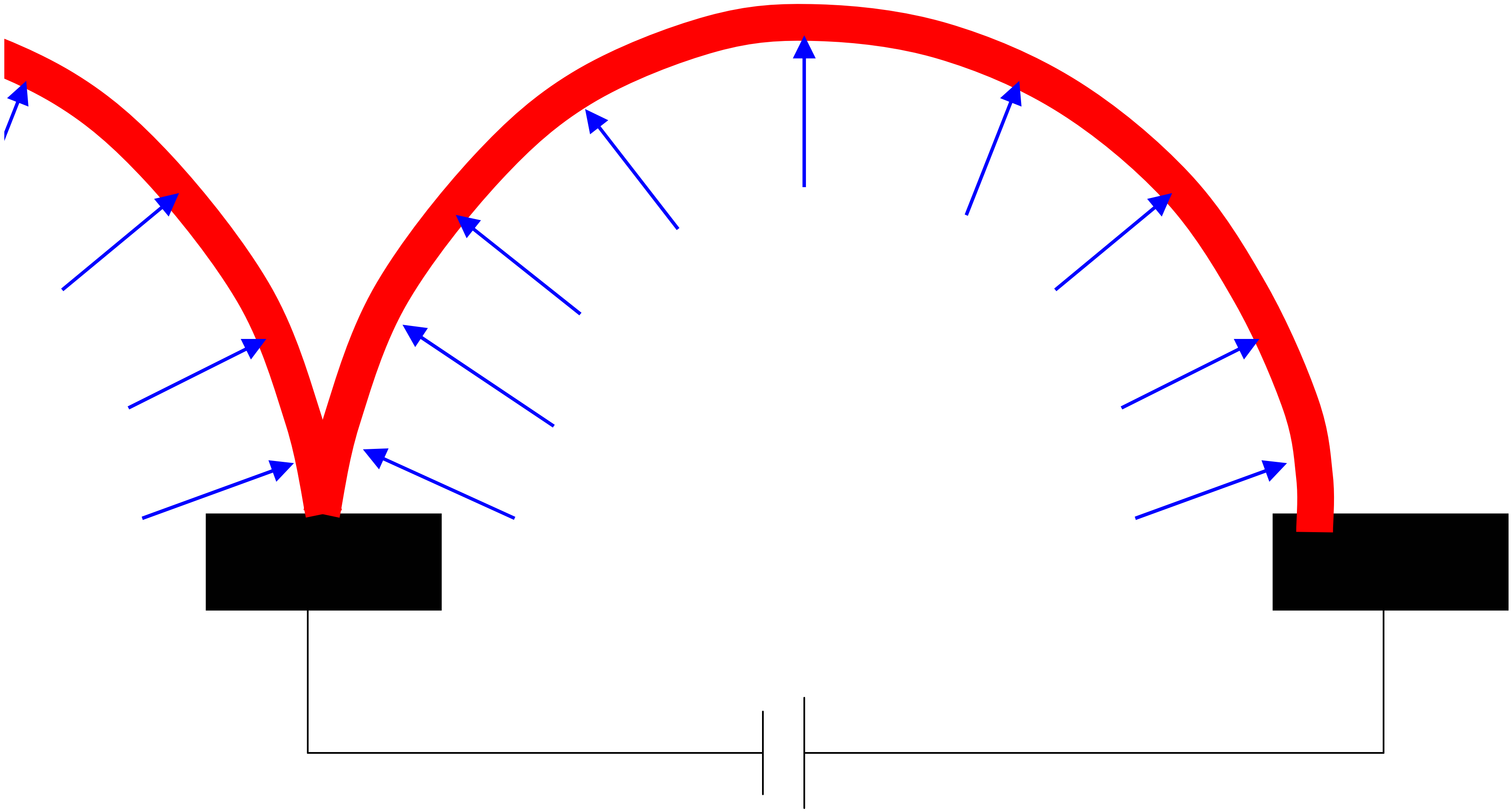


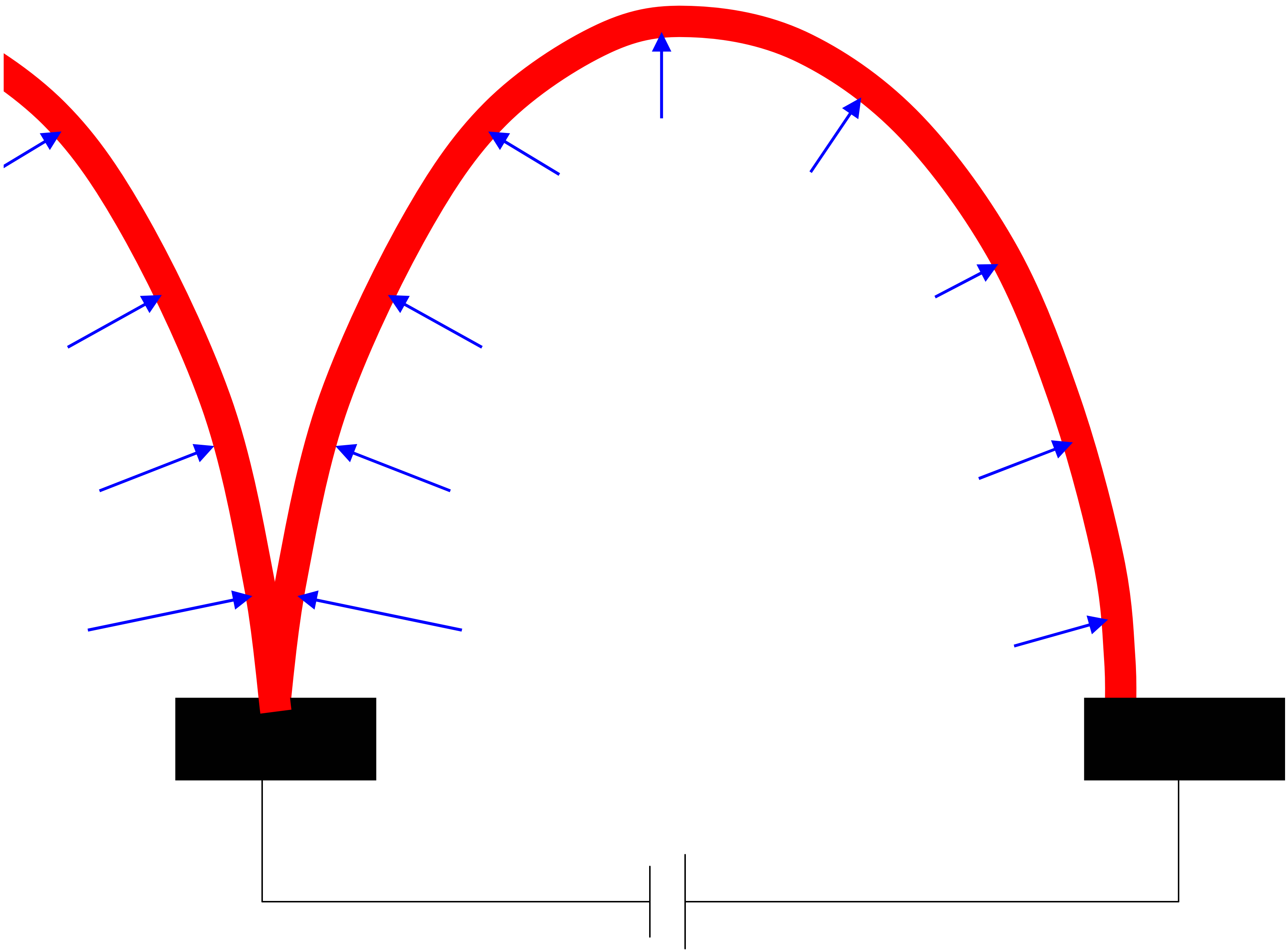
Spider leg evolution



Central column jet formation

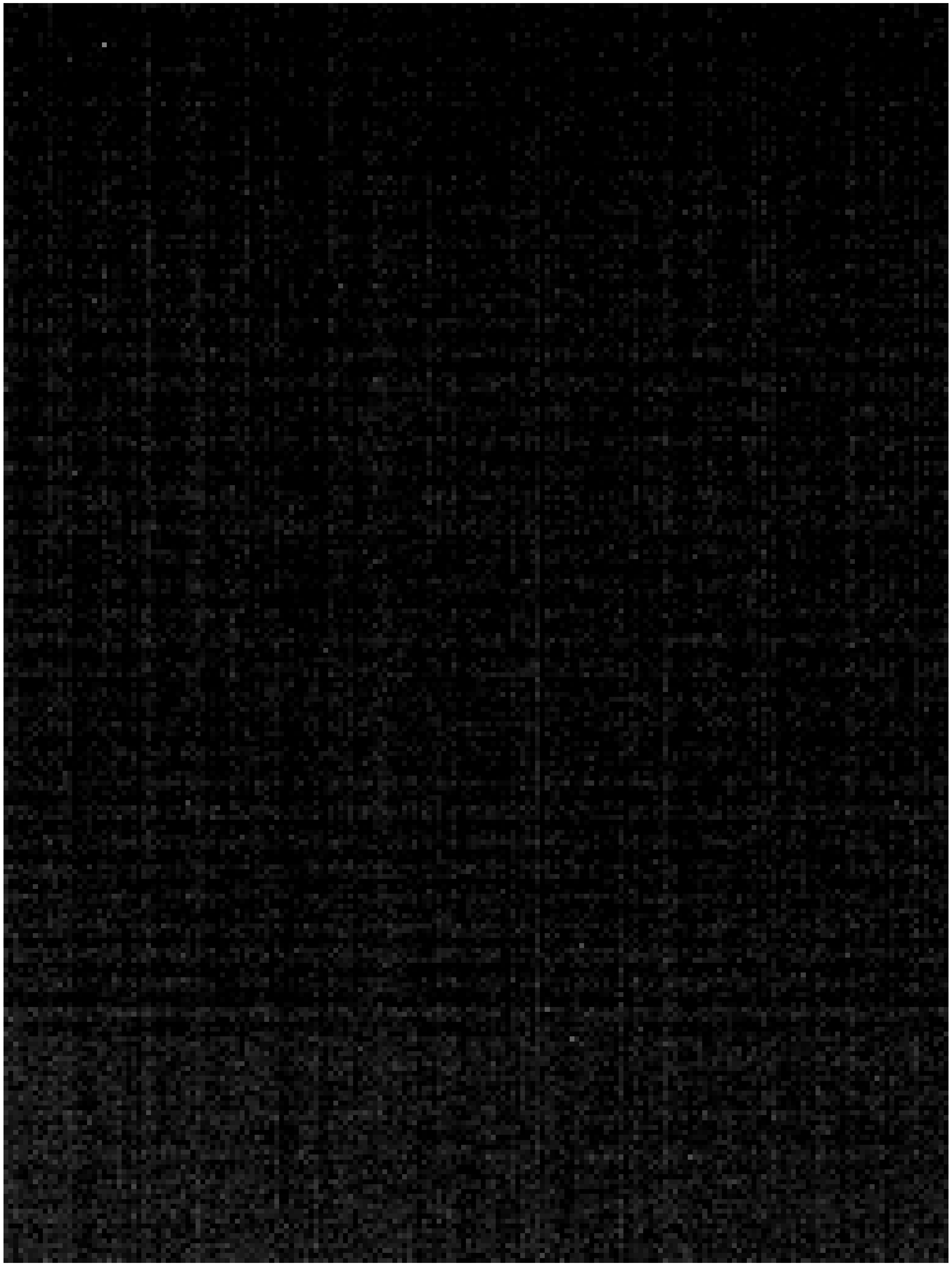
hoop force increases major radius,
form central column jet





Gas source is crucial

- spheromak mass ingested at Alfvenic velocity
- neutral density profile
  - determined by thermal gas jet
  - must be adequate for breakdown
- plasma density profile
  - determined by MHD pumping
  - no relation to initial neutral gas profile



Plasma jets from nozzles

Nitrogen injected from disk
gas nozzles

Neon injected from annulus
gas nozzles

Four (of eight)
outer nozzles valved off

10 million frames/sec

Summary

1. Kink instability fundamental to relaxation, topological evolution

2. Gas source of critical importance

3. High speed inflows (jets)

4. Stagnation of jet inflow leads to collimated flux tube

5. Uniform plasma assumption not appropriate

Publications

Observation/identification of kink instability:

"*A laboratory plasma experiment for studying magnetic dynamics of accretion discs and jets*", S. C. Hsu & P. M. Bellan,

MONTHLY NOTICES ROYAL ASTRONOMICAL SOCIETY **334**, 257 (2002)

Kink-induced toroidal-to-poloidal flux conversion:

"Experimental identification of the kink instability as a poloidal flux amplification mechanism for coaxial gun spheromak formation"

S. C. Hsu & P. M. Bellan,

PHYS. REV. LETTERS, 90 (21): art. no. 21500 (2003)

Theory of jet acceleration and collimation:

"Why current-carrying magnetic flux tubes gobble up plasma and become thin as a result",
P. M. Bellan,

PHYS. PLASMAS **10** Pt 2, 1999 (2003)

Measurements of jet acceleration and collimation:

-manuscript to be submitted shortly

-reports measurements of:

neutral density profile (fast ion gauge)

jet velocity (Doppler shifts, high speed movies)

plasma density (Stark broadening)